Data Science for Water Justice

Climate Change and Drought in the Colorado River Basin

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Water Justice Landscape

An overview of the intersection between climate change, water resources, and environmental justice with an assessment of where data science can foster meaningful progress towards water justice.

Executive Summary

There is increasing evidence that climate change is shifting the distribution of water on the planet - altering the global water cycle and increasing its intensity and unpredictability.[1] Alterations in this vital resource have cascading effects for all of society and the ecosystems with which we are entwined - including flooding, monsoons, sea level rise, droughts and entire ecosystem dynamic shifts.[2] In addition to the chaos of a changing water resource, the global demand for fresh water continues to grow as our agricultural systems and cities expand.[3] And woven amongst the threads of this issue is the fact that the impacts of climate change on water resources and the ability to adapt to them are not equally felt due to systemic social inequalities across the world[4], fostering new[5] and exacerbating existing water justice challenges.[6] To meet this challenge, actors from nearly every scale and sector have taken a piece of the puzzle. Some strategies focus on acute relief solutions such as providing bottled water when quality is threatened, as recently happened in Jackson, Mississippi during a flood event.[7] Similarly, but working towards longer term solutions, some organizations focus on establishing running water for increased water security, like the DigDeep Navajo Water Project.[8] Other strategies work on large scale drivers of water justice issues such as quantifying and codifying water rights (e.g., UN General Assembly recognizing water as a human right[9]) or infusing water infrastructure funds to support historically excluded or underserved communities (e.g., Water and Environment Program of the USDA[10]).

Data science can enter across this spectrum of work as a key ally, elevating and centering the pursuit of equity amidst the challenge of a changing water landscape.[11] Data, when created, analyzed and employed with attention to justice, can serve as an agent for meaningful impact, both in the ability to identify overlooked water challenges and in support of transformative adaptation solutions for those that need them most. Indeed, others

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[1] IPCC. (2021). Summary for policymakers. In Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change, edited by V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Pe´an, S. Berger, N. Caud, et al. Cambridge, UK: Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf. Hereafter IPCC (2021)

[2] IPCC (2021)

[3] Fioret, C. (2022). Water Justice as Socioenvironmental Justice. *Ethics, Policy & Environment*, 1-16.https://doi.org/10.1080/21550085.2022.2090211. Hereafter Fioret, C. (2022) ; Vorosmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global water resources: vulnerability from climate change and population growth. *Science*, *289*(5477), 284-288. https://doi.org/10.1126/science.289.5477.284

[4] Cardona, O. D. M. K. van Aalst, J., Birkmann, M., Fordham, G., McGregor, R., Perez, R. S., Pulwarty, E. L. F., Schipper, & Sinh, B. T. (2012). Determinants of risk: Exposure and vulnerability. In Managing the risks of extreme events and disasters to advance climate change adaptation, edited by C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, et al., 65108. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge, UK and New York, NY: Cambridge University Press. Hereafter Cardona, O., et al. (2012)

[5] Fioret, C. (2022).

[6] Mills-Novoa, M., Boelens, R., & Hoogesteger, J. (2022). Climate change and water justice. In Letcher, T. eds (2022) *Water and Climate Change* (pp. 399-418). Elsevier. Hereafter Mills-Novoa, M., et al. (2022)

[7] Vera, A., Hanna, J., & Salahieh, N. (2022, August 31). *Jackson, Mississippi, water: The water crisis has gotten so bad, the city temporarily ran out of water to give to residents*. CNN. https://www.cnn.com/2022/08/30/us/jackson-water-system-failing-tuesday/index.html

[8] *Navajo Water Project*. (n.d.). DigDeep. Retrieved July 28, 2022, from https://www.navajowaterproject.org/

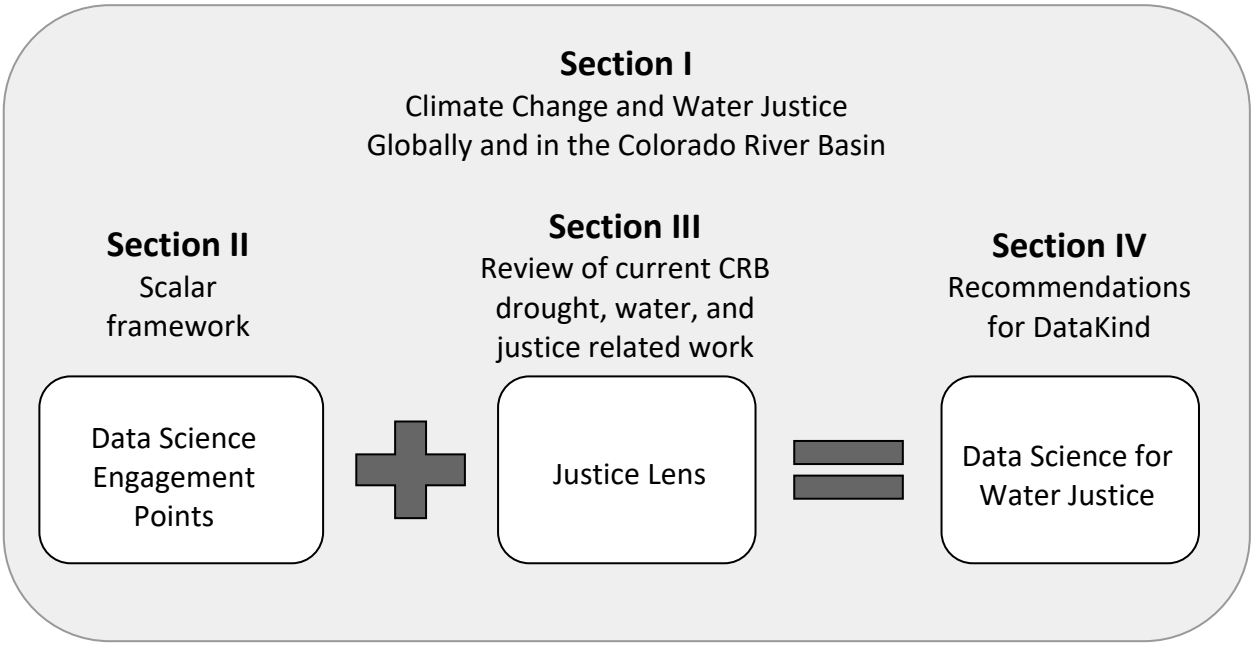
[9] United Nations. (n.d.). *The human right to water*. Water for Life Decade. Retrieved August 10, 2022, from https://www.un.org/waterforlifedecade/human_right_to_water.shtml

[10] USDA. (2015, June 1). *Water & Environmental Programs*. Rural Development. https://www.rd.usda.gov/programs-services/water-environmental-programs

[11] Gutierrez, M., & Bryant, J. (2022). The Fading Gloss of Data Science: Towards an Agenda that Faces the Challenges of Big Data for Development and Humanitarian Action. *Development*, *65*(1), 80-93. Hereafter Gutierrez, M., & Bryant, J. (2022)

have recognized the value of data science in tackling water injustices. For example, NASA has worked with the Navajo Nation to develop a drought monitoring tool that meets their needs in responding to localized drought conditions.[12] Analytic firms are using satellite data to foster precision agriculture[13], increasing efficiencies for water inputs that can help reduce overall demand and thus what is available to other water users. And in cases of pollution, machine learning has been used to detect lead in water pipes in Flint, MI, crucial work for improving the disproportionate impacts this lead pollution has had for the city's Black residents.[14]

While this challenge is global in scale, centering justice in the search for solutions to water issues within the climate change space necessitates paying close attention to local contexts. As such, this paper narrows in on one of the most pressing issues in the U.S. - the dynamics of climate change and drought in the Colorado River Basin. The following diagram provides an overview of the organization and direction of this landscape. The first section details the context in which the landscape is operating with an overview of the global climate change and water justice challenge then focuses in on the Colorado River Basin as a representative case study microcosm of water issues in the United States. Sections two through four operationalize this context by providing a framework from which to think about data science engagement, reviewing the current work being done and applying a justice-centered analysis of that work to finally provide the specific areas in which data science can engage with the water justice in the Colorado River Basin. Focusing on this particular water resource will provide an emblematic data science for water justice platform from which to launch other initiatives that can foster an equitable, resilient, and regenerative future.



[12] NASA. (n.d.). *Navajo Drought Tool User Guide*. NASA-Navajo Drought Severity Tool. Retrieved September 8, 2022, from https://wwao.jpl.nasa.gov/water-portfolio/water-projects/nasa-navajo-drought-severity-tool-user-guide/

[13] E.g., see work by Satyukt

[14] BlueConduit (2019, September 11). *The Atlantic: How Machine Learning Found Flint's Lead Pipes*. BlueConduit. https://blueconduit.com/post/the-atlantic-how-machine-learning-found-flints-lead-pipes/

Section I: Overview of the Challenge

The Global Water Challenge Under Climate Change

Water is vital to all life on the planet, interwoven into every layer of how the biosphere (i.e., all parts of the planet occupied by life) as we know it functions.[15] Society has always sought water as a foundation upon which to grow, relying on it to follow predictable patterns and paths that can be leveraged or managed, responding to shifts as they arrived.[16] But there is growing evidence that human-induced climate change is shifting the physical distribution of water on the planet in a wholly unprecedented way, creating a more unpredictable water cycle[17], and with it, a lack of security in the water landscape we are used to and rely on. The availability of water for human use is increasingly uncertain, both due to climate change variability as well as socio-economic and political drivers[18], and compounded by growing global demand.[19] As of 2020, a total of 2 billion people do not have access to reliable, safe, and secure water sources, the majority of which are in rural areas.[20] Even in the U.S., which is not perceived as suffering from lack of access to basic resources, 2 million people do not have running water or a working toilet at home.[21] This reality is why the UN defined its Sustainable Development Goal 6 as "ensuring availability and sustainable management of water and sanitation for all".[22]

Beyond availability, the impacts of a changing water cycle on all other systems on the planet, with knock on effects for society, are becoming more extreme.[23] Indeed, water - too much, too little, or too intense - is the way communities most often experience the sharp, painful impacts of a changing climate, through droughts, floods, and extreme weather events.[24] There are slower, more insidious changes in the water cycle as well, their pace often creating complacency and a mindset that the problem can be solved tomorrow because such changes tend to impact the ecosystems humans rely on first. A warmer planet means more evaporation from soils, drying and hardening them over time, reducing plant life, increasing fire risk, and altering entire landscapes.[25] A warmer atmosphere also holds more moisture, increasing the intensity of precipitation[26], even while the hotter and

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[15] Letcher, T. M. (Ed.). (2022). *Water and Climate Change: Sustainable Development, Environmental and Policy Issues*. Elsevier.

[16] Vuorinen, H. S., Juuti, P. S., & Katko, T. S. (2007). History of water and health from ancient civilizations to modern times. *Water Science and Technology: Water Supply*, *7*(1), 49-57. https://doi.org/10.2166/ws.2007.006

[17] IPCC. (2021)

[18] Sultana, F. (2018). Water justice: Why it matters and how to achieve it. *Water International*, *43*(4), 483-493.https://doi.org/10.1080/02508060.2018.1458272 Hereafter Sultana, F. (2018)

[19] UN-Water (2019). *UN World Water Development Report 2019*. Retrieved Aug 12, 2022, from https://www.unwater.org/publications/un-world-water-development-report-2019

[20] World Health Organization and UNICEF (2021). Progress on household drinking water, sanitation and hygiene 2000-2020: Five years into the SDGs. Geneva. https://washdata.org/sites/default/files/2021-07/jmp-2021-wash-households.pdf.

[21] DigDeep, & U.S. Water Alliance. (2019). *Closing the water access gap in the United States: A National action plan*. https://www.digdeep.org/s/Dig-Deep_Closing-the-Water-Access-Gap-in-the-United-States_DIGITAL_compressed-2hyx.pdf

[22] United Nations.(n.d.). *THE 17 GOALS - Sustainable Development*. Department of Economic and Social Affairs. Retrieved July, 30, 2022, from https://sdgs.un.org/goals

[23] UN-Water. (2010). Climate Change Adaptation: The Pivotal Role of Water. Policy and Analytical Briefs.https://www.unwater.org/publications/climate-change-adaptation-pivotal-role-water/. Hereafter UN-Water (2010)

[24] UN-Water. (2010).

[25] Overpeck, J. T., & Udall, B. (2020). Climate change and the aridification of North America. *Proceedings of the national academy of sciences*, *117*(22), 11856-11858. Hereafter Overpeck, J.T. & Udall, B. (2020)

[26] IPCC. (2008). Technical Paper VI. In: Climate Change and Water (B.C. Bates, Z.W. Kundzewicz, S. Wu and J.P. Palutikof, eds). Geneva, IPCC Secretariat, 210 pp.

dryer periods slow groundwater recharge and melt glaciers and snowpack, reducing overall flow and availability of water over time.[27] These acute and chronic water cycle pressures often collide, creating particularly devastating impacts, the ones that tend to command the most attention. The flooding of the American Southwest in July 2022[28] is thought to be a result of the interaction between the increased precipitation via more atmospheric moisture on top of a drought that has created dry soils, reducing in their ability to absorb large rainfall amounts.[29] In fact, in the last year alone, the urgency of addressing water-related climate change events could not be more poignant, with numerous acute crises and chronic issues reaching tipping points across the world.

Jackson, MO - Massive summer flooding has threatened water infrastructure and quality

Pakistan - The monsoon season has been particularly heavy, resulting in widespread floods and devastation

Germany - Increasing drought conditions have increased stakeholder conflicts over water use

Iraq - Increasing drought and aridification is fostering migration and food insecurity

Italy - Drought has forced emergency status in the country

Global – Growing conflict between lithium extraction for EV technology to combat climate change and impacts on water use and pollution

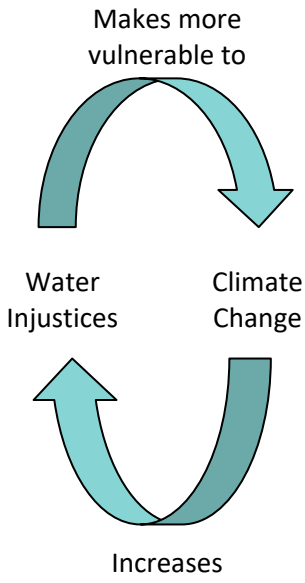
http://www.ipcc.ch/publications_and_data/publications_and_data_technical_papers_climate_change_and_water.htm. Hereafter IPCC (2008).

[27] UN-Water. (2010).

[28] Freedman, A. (2022). Climate whiplash: Southwest swings from drought to flood. *Wired.* Retrieved Aug 19, 2022, from https://www.axios.com/2022/08/19/southwest-flooding-drought-arizona-new-mexico

[29] Katwala, A. (2022). How Long Droughts Make Flooding Worse. *Wired*. Retrieved Aug 22, 2022, from https://www.wired.com/story/drought-causing-floods/

Water and Justice



At the heart of this challenge is the fact that the impacts of a water stressed world are not equally felt due to underlying inequalities, socio-political, and economic factors that create differential vulnerability.[30] It is very likely that the most extreme climate change impacts will occur in tropical regions.[31] This speaks to a Global North versus Global South disparity that has long been recognized - the largest contributors to the greenhouse gases that have fostered human-caused climate change are not those who will suffer most from its effects.[32] Not only does climate change create water injustices through its differential impacts, but the injustices these communities already face make them more vulnerable to climate change's impacts on water.[33] Thus, it is a mistake to point the finger at climate change as the origin of water justice issues, rather climate change and water justice are tied in a feedback loop.

Discussing justice issues within water governance has its own long history[34], but water justice is also part of the discourse addressing issues of underrepresentation in environmental decision making, disproportionately felt environmental risks and burdens, and unequal access to resources for adapting to environmental challenges, including climate change.[35] Collectively, these questions emerged in the U.S. context as part of the environmental justice movement, which developed at a local scale in the 1970s after a report revealed the unequal distribution of toxic waste sites in Warren County, NC in communities of color.[36] This was a watershed moment that catalyzed a social movement toward fostering the equal share of environmental benefits and burdens. The definition, and the movement's causes, expanded over the years, eventually linking up with the philosophies and approaches of other movements like food justice, indigenous rights and sovereignty, and expanding to topics like transportation and urban development.[37] It also arguably formed the foundation for climate justice at a global scale, as seen in the Climate Justice Summit during the COP6, which enumerated similar causes and concerns and their linkages between local level issues and the global impacts of climate change.[38] The links between environmental and climate justice further solidified after Hurricane Katrina in the

[30] Sultana, F. (2018).

[31] WWDR. (2020). United Nations World Water Development Report. United Nations World Water Assessment and UN-Water, UNESCO. Routledge. https://unesdoc.unesco.org/ark:/48223/pf0000372985.locale5en.

[32] Althor, G., Watson, J. E. M., & Fuller, R. A. (2016). Global mismatch between greenhouse gas emissions and the burden of climate change. Scientific Reports, 6(1), 20281. https://doi.org/10.1038/srep20281

[33] Mills-Novoa, M., et al. (2022).

[34] E.g., see Freyfogle, E. T. (1986). Water justice. *U. Ill. L. Rev.*, 481.; Neal, M. J., Lukasiewicz, A., & Syme, G. J. (2014). Why justice matters in water governance: some ideas for a 'water justice framework'. *Water Policy*, *16*(S2), 1-18. https://doi.org/10.2166/wp.2014.109 . Hereafter Neal, M.J. et al. (2014)

[35] Zwarteveen, M. Z., & Boelens, R. (2014). Defining, researching and struggling for water justice: some conceptual building blocks for research and action. *Water international*, *39*(2), 143-158. https://doi.org/10.1080/02508060.2014.891168

[36] Schlosberg, D., & Collins, L. B. (2014). From environmental to climate justice: climate change and the discourse of environmental justice. *Wiley Interdisciplinary Reviews: Climate Change*, *5*(3), 359-374. https://doi.org/10.1002/wcc.275 Hereafter Schlosberg, D., & Collins, L. B. (2014); McLean, J. (2007). Water injustices and potential remedies in indigenous rural contexts: a water justice analysis. *The Environmentalist*, *27*(1), 25-38.https://doi.org/10.1007/s10669-007-9012-0

[37] Schlosberg, D., & Collins, L. B. (2014).

[38] Ibid.

U.S., making clear that the immediate health concerns of toxic emissions were also tied to the changing climate and the extreme events it could produce.[39] Water justice can ultimately be seen as a facet of these social movements, focused on water resources, and similarly tied to local scale issues like the first wave of environmental justice, but also expanding in recent years to include climate change.[40]

Within this discussion, it is easy to take for granted the concept of justice itself and the myriad ways in which it is understood. While this paper cannot present a full discussion of the various philosophical underpinnings of defining justice, it is nonetheless important to point out that it is not a universal concept.[41] Definitions of justice range from viewing it as the greatest amount of good for the most people (i.e., utilitarianism) to equation with fairness and equal distribution (i.e., Rawlsian theory of justice) to the ability of people to secure their basic needs (capabilities approach).[42] This landscape paper conceptualizes water justice via the following definition, which emphasizes a relational view of justice given the ever shifting nature of climate change and its impacts on specific contexts:

> *The interactive societal and academic endeavor to critically explore water knowledge production, allocation and governance and to combine struggles against water-based forms of material dispossession, cultural discrimination, political exclusion and ecological destruction, as rooted in particular contexts*.[43]

As a reflection of water itself, issues of water (in)justice span geographic and temporal scales, acute and chronic pressures on ecosystems and humans, with specific dynamics that reflect the socio-political and ecological history of a given area. This specificity is why addressing issues of justice must be tied to context, which the latter half of this landscape will do. One of the most recent examples of a water justice issue was already referenced - the flooding of Jackson, Mississippi at the end of August 2022. After days of heavy rainfall, the kind of precipitation predicted to become more frequent because of climate change, the water treatment facilities failed, putting the entire city's water safety at risk and necessitating urgent deliveries of bottled water to residents.[44] Yet, this crisis is not one formed purely from climate change - water issues have plagued the city for decades from broken water mains to sewage leaks. The majority of Jackson's residents are Black and have faced systemic inequalities and disinvestment in public infrastructure for years, a pattern tied to the city's legacy of racism and the subsequent economic and racial disparities it has produced.[45] The lack of investment in infrastructure now means the cost to repair and improve it during crises rises drastically, making future-thinking

[39] Ibid.

[40] Mills-Novoa, M., et al. (2022).

[41] Ibid.

[42] Ibid.

[43] Ibid. p.404

[44] Dennis, B., & Kaplan, S. (2022, August 31). *Jackson water crisis signals a bigger climate casualty.* The Washington Post. https://www.washingtonpost.com/climate-environment/2022/08/31/jackson-water-crisis-mississippi-floods/

[45] Perry, A. M., Kane, J., & Romer, C. (2021, March 26). *In Jackson, Miss., a water crisis has revealed the racial costs of legacy infrastructure*.Brookings.https://www.brookings.edu/blog/the-avenue/2021/03/26/in-jackson-miss-a-water-crisis-has-revealed-the-racial-costs-of-legacy-infrastructure/

investments all the more difficult.[46] In this way, Jackson's ills are a prime example of the vicious cycle of water injustices and climate change, and reflect other similar scenarios throughout the U.S., where a history of racism has produced systemic inequalities that affect communities' abilities to adapt to climate change and other crises (i.e., Flint, Michigan's water crisis[47]).

Another water justice issue less commonly discussed is the water pollution resulting from industries that produce the greenhouse gases that are spurring climate change. In East Orosi, California, the groundwater is polluted by nitrates, affecting the quality of drinking water available to the majority low-income and Latino communities that rely on it.[48] These nitrates are a nonpoint source pollutant from the agricultural industry in the region, a by-product of fertilizer application.[49] In the coal industry focused Appalachia region, coal slurry storage has leaked into rivers and streams in multiple catastrophic events, risking water quality for both humans and the surrounding ecosystems.[50] There are also noted health disparities - ranging from increased cancer rates to increased mortality - for the low income communities in the Appalachia, which although difficult to tie directly to the coal industry itself, are nonetheless critical potential disparities to understand.[51]

Moving beyond the U.S., in South America water justice issues are emerging around agricultural water uses. Lake Poopó in Bolivia experienced an extreme drying period from 2014-2015, which disproportionately impacted the underrepresented and marginalized Urus indigenous peoples who rely on the lake for subsistence fishing and their livelihoods.[52] Large scale extractions of water for agriculture, mining, and urban uses played a large role in this drying period, with some suggesting these actors used the cover of climate change to obfuscate this role and allow their continued overuse.[53] A similar dynamic has played out in Piura, Peru as well where the Water Resource Law has shifted prioritizing water use to the agricultural export industry and climate change is being used to facilitate this shift and marginalize smaller landholders.[54]

Water justice issues also extend beyond direct use for human or industry consumption. In New Zealand, the draining of wetlands by colonial settlers has created a legacy of degraded supportive ecosystems that ultimately perpetuate injustices for Māori communities, impacting their health and well-being.[55] This example also intersects with the broader movement of fighting for water rights and sovereignty, which are often focused on

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[46] Ibid.

[47] Pauli, B. J. (2020). The Flint water crisis. *Wiley Interdisciplinary Reviews: Water*, *7*(3), e1420.

[48] Vanderwarker, A. (2012). Introduction: Water and environmental justice. In Christian-Smith, J., Gleick, P. H., Cooley, H., Allen, L., Vanderwarker, A., & Berry, K. A. (2012). *A twenty-first century US water policy*. Oxford University Press.

[49] Ibid.

[50] Sturgis, S. (2014, January 13). *WV water contamination exposes chemical hazards of coal power*. Facing South. https://www.facingsouth.org/2014/01/wv-water-contamination-exposes-chemical-hazards-of.html

[51] Zipper, C. E., & Skousen, J. (2021). Coal's legacy in Appalachia: Lands, waters, and people. *The Extractive Industries and Society*, *8*(4), 100990. https://doi.org/10.1016/j.exis.2021.100990

[52] Perreault, T. (2020). Climate change and climate politics: Parsing the causes and effects of the drying of Lake Poopo´, Bolivia. Journal of Latin American Geography, 19(3), 2646. Available from https://doi.org/10.1353/lag.2020.0070

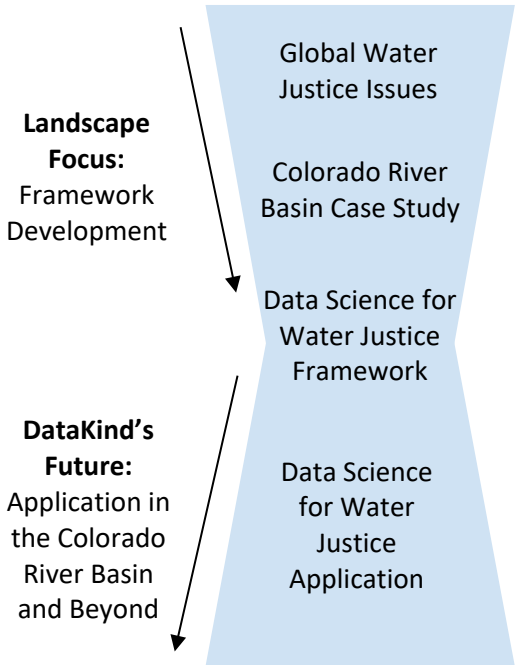
[53] Ibid.

[54] Mills-Novoa, M. (2020). Making agro-export entrepreneurs out of Campesinos: The role of water policy reform, agricultural development initiatives, and the specter of climate change in reshaping agricultural systems in Piura, Peru. Agriculture and Human Values, 37, 667682. https://doi.org/10.1007/s10460-019-10008-5

[55] Parsons, M., Fisher, K., & Crease, R. P. (2021). Remaking Muddy Blue Spaces: Histories of Human-Wetlands Interactions in the Waipā River and the Creation of Environmental Injustices. In *Decolonising Blue Spaces in the Anthropocene* (pp. 121-179). Palgrave Macmillan, Cham. https://doi.org/10.1007/978-3-030-61071-5_4

global Indigenous communities' struggles against the histories of colonialism, racism, marginalization, and other oppressive mechanisms that create unjust power dynamics between who controls, frames, and uses water and who is edged out of the resource. Indeed, this is central to the rest of the landscape's discussion on water justice issues within the Colorado River Basin. Another prominent example can be found in the struggle for sovereignty in the fight against the Dakota Access Pipeline in the US by a coalition of Tribes who argued that the pipeline would risk their right to safe water due to its proposed route along the Missouri River.[56] Similar conflicts over extractive industries and water rights, most often affecting communities with the least power, play out across the world, as seen with the Wayúu people and coal mining in Columbia,[57] water pollution from lithium mining in Chile,[58] and conflicts over land and water rights in gold mining in Mexico.[59]

This overview represents just a fraction of the water justice issues that are becoming increasingly apparent, and this landscape cannot conceivably cover all of them. It will instead focus the remainder of the paper on one specific water resource in the U.S. - the Colorado River Basin - and its associated climate change and water justice dynamics, serving as an exemplar case study and creating a framework for how data science can be leveraged for water justice in other geographies.



[56] Ratcliff, L. (2016). Water, Oil, and Tribal Sovereignty: The Fight for the Dakota Access Pipeline. *U. Denv. Water L. Rev.*, *20*, 125.

[57] Ulloa, A. (2020). The rights of the Wayúu people and water in the context of mining in La Guajira, Colombia: demands of relational water justice. *Human Geography*, *13*(1), 6-15. https://doi.org/10.1177/1942778620910894

[58] Jerez, B., Garcés, I., & Torres, R. (2021). Lithium extractivism and water injustices in the Salar de Atacama, Chile: The colonial shadow of green electromobility. *Political Geography*, *87*, 102382. https://doi.org/10.1016/j.polgeo.2021.102382

[59] Stoltenborg, D., & Boelens, R. (2016). Disputes over land and water rights in gold mining: the case of Cerro de San Pedro, Mexico. *Water International*, *41*(3), 447-467.https://doi.org/10.1080/02508060.2016.1143202

The Colorado River Basin

The Colorado River Basin (CRB) is a social-ecological system that provides a case study emblematic of many climate change accelerated water justice challenges - transboundary, multiple climate and social drivers, stakeholder conflicts, urban and rural differences, and underlying, historical issues of water rights and responsibilities. This system is one of the most crucial water resources in the United States, supporting over 40 million people across the seven states of Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming.[60] It is also home to over 30 indigenous Tribes[61] and a third of the entire U.S. Latino community.[62] It supports a $75 billion industry in recreation, 5.5 million acres of irrigation for agriculture, 30 endemic fish species, and vital ecosystems for bird migration[63]. Even though this complex social-ecological system contains immense cultural, environmental, and intrinsic value, its management has largely been focused on human-centered water consumption and allocation.[64] Divided into an upper basin and lower basin (Fig. 1), the region's surface water is governed by a collective group of treaties, compacts, and regulations called the Law of the River[65], which, among many other aspects, allocates water to each of the states in the basin (Fig. 2). [66] The largest water user, accounting for roughly 70% of total water usage, is agriculture.[67]

Fig. 1 - The Colorado River Basin[66]

[60] U.S.Bureau of Reclamation.(2021). Colorado River Basin SECURE Water Act Section 9503(c) Report to Congress.https://www.usbr.gov/climate/secure/docs/2021secure/basinreports/ColoradoBasin.pdf. Hereafter USBR (2021)

[61] *Who We Are*. (n.d.). Water and Tribes Initiative. Retrieved August 10, 2022, from https://www.waterandtribes.org/about-us

[62] *Colorado River*. (n.d.). American Rivers. Retrieved August 15, 2022, from https://www.americanrivers.org/river/colorado-river/

[63] *Protecting the Colorado River.* (n.d.). Western Resource Advocates.Retrieved August 22, 2022, from https://westernresourceadvocates.org/healthy-rivers-lakes/protecting-the-colorado-river/

[64] Kwon, K., & Gimbel, J. (2021). Quenching the thirst in the Colorado River Basin. Colorado Water Center - Colorado State University. https://watercenter.colostate.edu/wp-content/uploads/sites/91/2021/11/CoWC-CR-Papers-Final-11032021.pdf Hereafter Kwon, K., & Gimbel, J. (2021).

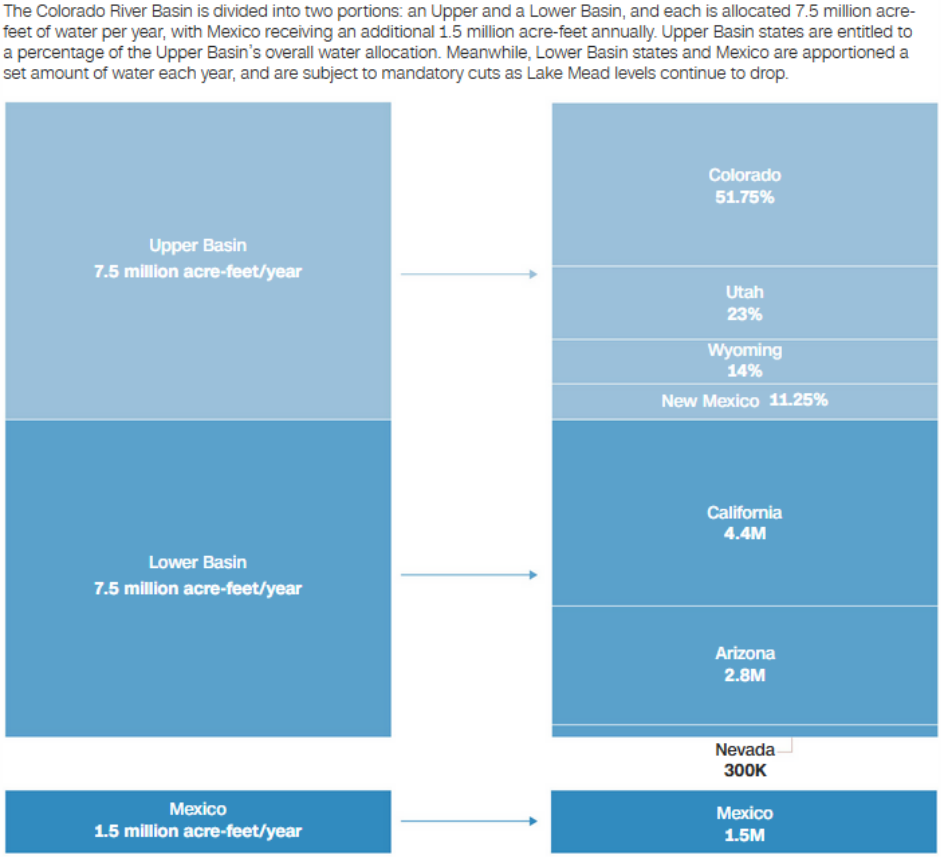
[65] *Law of the River*. (n.d.). Bureau of Reclamation: Lower Colorado Region. Retrieved September 7, 2022, from https://www.usbr.gov/lc/region/g1000/lawofrvr.html

[66] Nilson, E., & Ramirez, R. (2022, August 16). *New water cuts coming for Arizona, Nevada as Colorado River falls into Tier 2 shortage.* CNN. https://www.cnn.com/2022/08/16/us/colorado-river-water-cuts-lake-mead-negotiations-climate/index.html

[67] USBR (2021)

The Colorado River Basin, and the American southwest more generally, has been in a drought since 2000.[68] It is the worst in centuries, earning it the moniker of a megadrought.[69] There are two core drivers of this drought - climate change induced aridification[70] and increasing withdrawals to meet agricultural and municipal demands[71]- forces that combine to create a critical deficit. Climate change has shifted the water cycle in the CRB by shrinking snowpack, drying soils, and reducing ground water recharge.[72] The CRB is also experiencing some of the most rapid growth and development in the nation, with Nevada, Arizona, and Utah ranking as the top three fastest growing states in the US from 2000-2010.[73] On top of these core drivers is the additional pressure of overallocated water rights. The surface waters of the Colorado River Basin were divided up among seven states and Mexico in the 1920s based on calculations of flow from a wetter period (see Figure 3 below[74]), resulting in more water allocated (17.5 million acre-feet) than there typically is flowing through the basin in a given year (14.8 million acre-feet) and creating a fundamental gap between supply and demand.[75]

Fig. 2 - Colorado River Allocation[66]



[68] Williams, A.P., Cook, E.R., Smerdon, J.E., Cook, B.I., Abatzoglou, J.T., Bolles, K., Baek, S.H., Badger, A.M. & Livneh, B. (2020). Large contribution from anthropogenic warming to an emerging North American megadrought. *Science*, *368*(6488), pp.314-318. Hereafter Williams, A.P., et al. (2020).

[69] Williams, A.P., et al (2020).

[70] Overpeck, J. T., & Udall, B. (2020).

[71] USGS. (n.d.). *USGS Water Use Data for the Nation*. National Water Information System. Retrieved October 4, 2022, from https://waterdata.usgs.gov/nwis/wu; Babbitt Center for Land and Water Policy. (2022, August 10). *The Hardest Working River in the West*. ArcGIS StoryMaps. https://storymaps.arcgis.com/stories/2efeafc8613440dba5b56cb83cd790ba. Hereafter Babbitt Center for Land and Water Policy (2022)

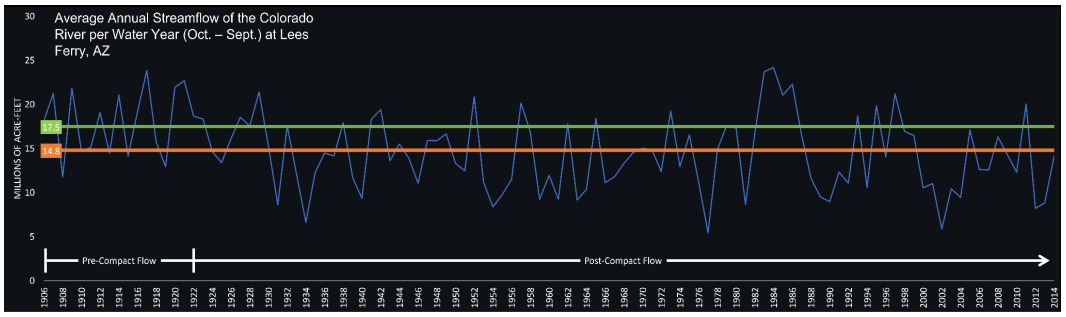
[72] Overpeck, J. T., & Udall, B. (2020).; Williams, A.P., et al. (2020).

[73] USBR (2021)

[74] Babbitt Center for Land and Water Policy (2022)

[75] American Rivers, & Western Resources Advocates. (2014). *Hardest Working River in the West: Common-Sense Solutions for a Reliable Water Future for the Colorado River Basin*. https://westernresourceadvocates.org/publications/the-hardest-working-river-in-the-west-colorado-river-basin/; Babbitt Center for Land and Water Policy (2022)

Fig. 3 - Colorado River Allocations vs. Flow over Time[74]



This deficit has generally been balanced by utilizing the basin's reservoir storage capacities, the continued development of the upper basin's apportionment, and strategies to reduce water use over the years.[76] In addition, a large portion of water rights held by the basin's Tribes has not been fully realized. As part of the Law of the River, Tribes are entitled to around one-fifth of the surface waters of the CRB, yet they have not used this full entitlement either due to the large bureaucratic barriers involved in resolving the rights or not consuming as much as is allocated.[77] Historically, these factors have allowed the overallocated basin to provide water to all, but it has now reached a tipping point. In the summer of 2022, Lake Mead and Lake Powell, the basin's two largest reservoirs, reached their lowest levels in decades, triggering the US Bureau of Reclamation to declare a Tier 2 shortage.[78] This shortage will cut water usage in the lower basin states, with Arizona taking the largest cut - 21% of its allocation - worsening an already harsh landscape for water users.[79]

These intersecting issues have spurred organizations like American Rivers to designate the Colorado River as the number one endangered river in the U.S.[80] The impacts of the drought are all encompassing for the region, affecting everything from household water access to the price of vegetables.[81] Since the agriculture industry is the largest water user in the CRB, it also stands to receive some of the largest impacts of the extended drought due to the threat of water scarcity and salt accumulation on crop growth[82], with models of continued drought conditions predicting substantial and increased crop loss.[83] There are also growing concerns within the energy sector, as the reservoirs and dams in the basin produce a substantial amount of hydropower that is at risk if their water levels fall too low.[84] Even the tech sector in the region might be impacted by a water scarce reality

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[76] USBR (2021)

[77] U.S. Bureau of Reclamation. (2018). Colorado River Basin Ten Tribes Partnership Tribal Water Study, Study Report. https://www.usbr.gov/lc/region/programs/crbstudy/tws/finalreport.html. Hereafter USBR (2018)

[78] Nilson, E., & Ramirez, R. (2022, August 16). *New water cuts coming for Arizona, Nevada as Colorado River falls into Tier 2 shortage.* CNN. https://www.cnn.com/2022/08/16/us/colorado-river-water-cuts-lake-mead-negotiations-climate/index.html

[79] Ibid.

[80] American Rivers. (2022). *Colorado River*. America's Most Endangered Rivers. https://endangeredrivers.americanrivers.org/colorado-river/

[81] USBR. (2021)

[82] MacDonald, G. M. (2010). Water, climate change, and sustainability in the southwest. *Proceedings of the National Academy of Sciences*, *107*(50), 21256-21262.

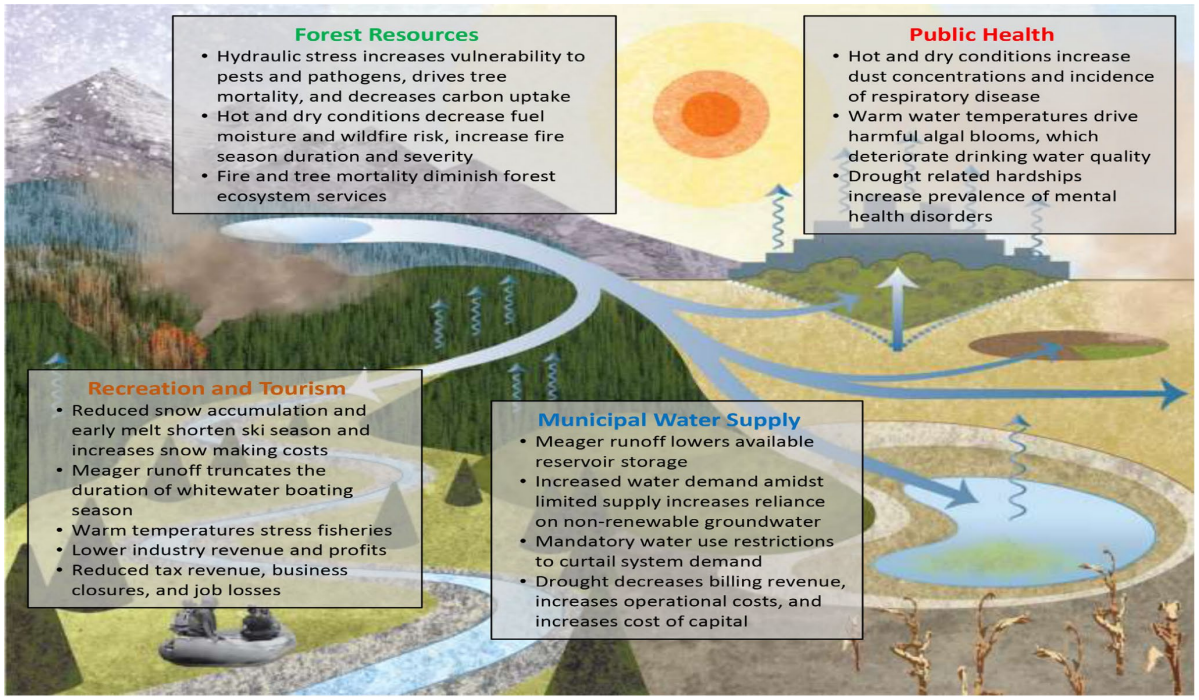
[83] McCoy, A. L., Jacobs, K. L., Vano, J. A., Wilson, J. K., Martin, S., Pendergrass, A. G., & Cifelli, R. (2022). The press and pulse of climate change: extreme events in the Colorado River Basin. *JAWRA Journal of the American Water Resources Association*. https://doi.org/10.1111/1752-1688.13021. Hereafter McCoy, A.L. et al. (2022)

[84] Penmetsa, V., & Holbert, K. E. (2019). Climate Change Effects on Solar, Wind and Hydro Power Generation. *2019 North American Power Symposium (NAPS)*, 1–6. https://doi.org/10.1109/NAPS46351.2019.9000213; Wadsack, K., & Acker, T. L. (2019). Climate change and future power systems: the importance of energy storage in reduced-hydropower systems in the American Southwest. *Clean Energy*, *3*(4), 241-250. https://doi.org/10.1093/ce/zkz030

because data centers use substantial amounts of water for cooling and water cuts can impact the cost and feasibility of this approach.[85]

Additional cross-cutting impacts include air quality health threats from increased dust and fire smoke, water quality threats from a changing water cycle, land subsidence due to increased ground water extraction and reduced recharge rates, and economic impacts to the robust outdoor recreation and tourism industries.[86] More in-depth reviews of these impacts can be found in key scholarship in the field[87], but it is clear that the drought touches everyone and everything in the CRB with ripple effects beyond its geography and over time (Fig 4). [88]

Fig. 4 - Impacts of Drought on Various Sectors in the Intermountain West[88]



[85] Copley, M. (2022, August 30). *Data centers, backbone of the digital economy, face water scarcity and climate risk*. NPR. https://www.npr.org/2022/08/30/1119938708/data-centers-backbone-of-the-digital-economy-face-water-scarcity-and-climate-ris

[86] Wlostowski, A. N., Jennings, K. S., Bash, R. E., Burkhardt, J., Wobus, C. W., & Aggett, G. (2022). Dry landscapes and parched economies: A review of how drought impacts nonagricultural socioeconomic sectors in the US Intermountain West. *Wiley Interdisciplinary Reviews: Water*, *9*(1), e1571.https://doi.org/10.1002/wat2.1571. Hereafter Wlostowksi, A.N., et al. (2022)

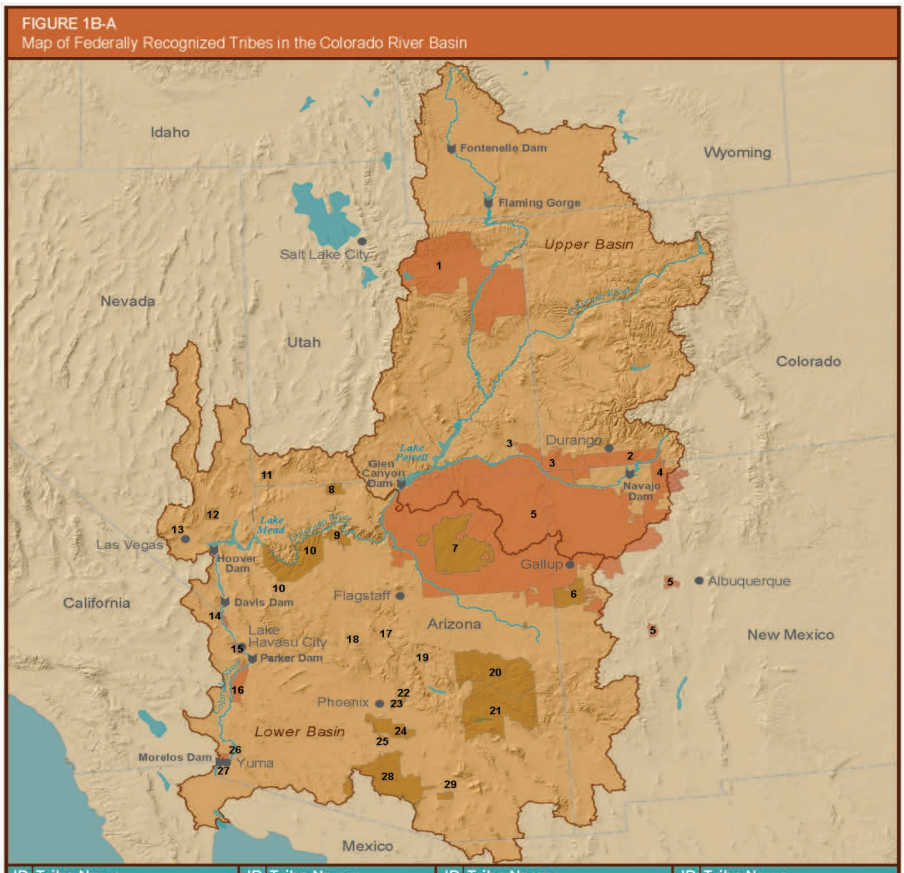
[87] Wlostowski, A. N., et al. (2022); McCoy, A. L., et al. (2022)

[88] Fig. 3 in Wlostowski, A. N., et al. (2022).

Water Justice in the CRB

Similar to the global scale discussion, water justice challenges in the CRB infuse nearly every component of the system. Its transboundary nature - international, interstate, interregional, intertribal - and profound role in the social and ecological functioning of the region have anchored the waters of the basin as a vital, if divisive, resource with stakeholders vying for control of its valuation and management.[89] This historical positionality has created a management legacy with vast disparities, perpetuating injustices in access and decision making that fall hardest on Tribal [90] communities in particular.[91] There are indeed other important cases of water injustices within the basin that are important to acknowledge - similar dynamics play out with Latino/a, immigrant, Black, and low-income communities, including their intersections, but this discussion will focus on the Tribes that call the CRB their home (see Fig. 5 for map[92]).

Fig. 5 - Map of the Federally Recognized Tribes of the CRB[92]



ID	Tribe Name	ID	Tribe Name	ID	Tribe Name	ID	Tribe Name
1	Ute Indian Tribe of the Uintah and Ouray Reservation	9	Havasupai Tribe	15	Chemehuevi Indian Tribe	23	Salt River Pima-Maricopa Indian Community
2	Southern Ute Indian Tribe	10	Hualapai Indian Tribe	16	Colorado River Indian Tribes	24	Gila River Indian Community
3	Ute Mountain Ute Tribe	11	Shivwits Band of Paiute Indian Tribe	17	Yavapai-Apache Nation	25	Ak-Chin Indian Community
4	Jicarilla Apache Nation	12	Moapa Band of Paiute Indians	18	Yavapai-Prescott Indian Tribe	26	Quechan Indian Tribe
5	Navajo Nation	13	Las Vegas Tribe of Paiute Indians	19	Tonto Apache Tribe	27	Cocopah Indian Tribe
6	Zuni Tribe	14	Fort Mojave Indian Tribe	20	White Mountain Apache Tribe	28	Tohono O'odham Nation
7	Hopi Tribe			21	San Carlos Apache Tribe	29	Pascua Yaqui Tribe
8	Kaibab Band of Paiute Indians			22	Fort McDowell Yavapai Nation		

In broad terms, Tribes are experiencing physical, social, and economic driven water access issues.[93] There is a lack of access to water because of the drought itself, but also because of the historic socio-political injustices that have positioned Tribes as secondary water users. Social and economic isolation and exclusion has resulted in reduced representation in decision making, lack of infrastructure that provides physical access to clean and safe water, and inadequate

[89] Babbitt Center for Land and Water Policy (2022)

[90] There is no universally accepted term for these communities - also called Native, Indigenous, First Peoples, and Indian. This paper refers to them as Tribal, reflecting the majority of the work produced in the CRB

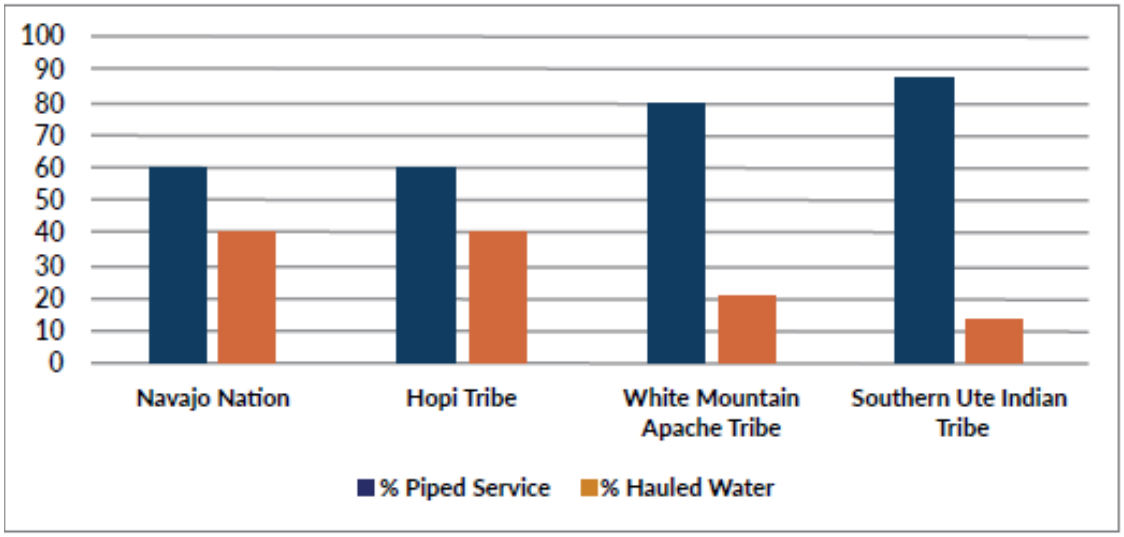
[91] Tanana, H., Garcia, J, Olaya, A., Colwyn, C., Larsen, H., Williams, R., & King, J. (2021). Universal access to clean water for Tribes in the Colorado River Basin. Water & Tribes Initiative: Colorado River Basin. University of Montana. Retrieved Aug 15, 2022 at https://www.naturalresourcespolicy.org/docs/water-tribes/wti-full-report-4.21.pdf. Hereafter Tanana, H., et al. (2021)

[92] USBR (2018)

[93] Tanana, H., et al. (2021)

funding for quality monitoring and maintenance.[94] This is manifest in the fact that Native households in the U.S. are 19 times more likely to lack plumbing than white households[95], forcing them to utilize unregulated sources of water.[96] In the CRB, Navajo Nation households are 67 times more likely to lack running water than other households in the U.S.,[97] often relying instead on hauled water (see Fig. 6 for distribution[98]) that is 71 times more expensive than piped water.[99] As climate change continues to advance the aridification of the region, reducing the flow of water that reaches communities and slowing the recharge of groundwater, the underlying biophysical drivers of water scarcity are predicted to become all the more dire.

Fig. 6 - % Households with Piped vs. Hauled Water for four Tribes of the CRB[98]



It is not water access alone that is affected by the vicious cycle of climate change and water injustices in the CRB. There are drastic secondary health and wellbeing consequences for Tribal communities as well, resulting from water scarcity, water contamination and quality issues, and lack of investment in infrastructure and maintenance. For instance, many families ultimately ration their scarce water, making choices like using processed food and sugary drinks since they are less water intensive, which in turn creates an environment ripe for increases in diabetes.[100] Historic mining operations have also left a mark on the region. Uranium mining, spurred by the Manhattan Project of the mid-century, has increased arsenic contaminants in the groundwater,[101] exacerbating the already naturally occurring arsenic in the drinking supply of the Hopi tribe where 75% residents are estimated to be drinking contaminated water.[102] The aging and poorly funded

[94] Ibid.

[95] DigDeep, & U.S. Water Alliance. (2019). *Closing the water access gap in the United States: A National action plan*. https://www.digdeep.org/s/Dig-Deep_Closing-the-Water-Access-Gap-in-the-United-States_DIGITAL_compressed-2hyx.pdf

[96] Lewis, J., Hoover, J., & MacKenzie, D. (2017). Mining and environmental health disparities in Native American communities. *Current Environmental Health Reports*, *4*(2), 130-141 https://doi.org/10.1007/s40572-017-0140-5. Hereafter, Lewis, J. et al. (2017).

[97] Ibid.

[98] Fig 6 from Tanana, H., et al. (2021).

[99] Tanana, H. et al. (2021)

[100] Ibid.

[101] Lewis, J. et al. (2017).

[102] Tanana, H., Combs, J., & Hoss, A. (2021). Water is life: law, systemic racism, and water security in Indian Country. *Health Security*, *19*(S1), S-78. https://doi.org/10.1089/hs.2021.0034

infrastructure can also present risks - the public water systems on Native American reservations often have double the violations of Safe Drinking Water Act regulations as the rest of public water systems.[103] This same aging infrastructure also leaks, wasting the precious water that is already hard to come by and hampering economic growth. The Colorado River Indian Tribes, who rely on agriculture for their livelihoods, have been unable to repair and expand irrigation, reducing their ability to farm in a competitive manner.[104]

Ultimately, a chronic issue that underlies many of these water risks and their impacts on Tribes is the under appropriation of funds by the US government, impeding the fulfillment of their trust responsibility to Tribes.[105] This lack of financial prioritization puts an already vulnerable group into an even more fraught position, reducing their ability to be resilient in the face of climate change. On top of this disinvestment is the centuries long battle over water rights in the CRB. The Tribes of the basin did not have legally recognized water rights until the Winters Doctrine of 1908, which established Native water rights in the U.S. as implicit in the establishment of reservation land.[106] This meant Tribal water rights in the CRB often precede those of non-Native water users because reservations were usually established before these users claims, allowing many Tribes seniority under prior appropriation.[107] However, most of these rights were not originally quantified and must go through an adjudication process that is onerous and creates administrative impediments to making them anything more than paper rights.[108] Even more, fulfilling these rights in the CRB presents large uncertainty for future water management and demand as Tribes hold a significant portion of water allocation, but do not utilize it.[109]

An example of how these elements - climate change, water justice, and water rights - intersect in the CRB can be found in the debate for remedying the impact of coal mining in the region. Tribal communities have recently spoken out against the largest U.S. coal company, Peabody Energy Corp, for its role in withdrawing massive amounts of water from the Navajo Aquifer during its coal mining operations, which shuttered in 2019 but used to supply the largest coal-fired plant west of the Mississippi River and provided power predominantly to Arizona, California, and Nevada.[110] This plant, the Navajo Generating Station, was also one of the top three greenhouse gas emitters in the U.S.[111] While the company disputes the claim, Tribes argue that aquifer withdrawals have further strained water availability in the region and the company is responsible for restoring the waters of the aquifer.[112] In this example, the coal industry not only contributes directly to the greenhouse gases that fuel climate change, but also demonstrates the power imbalance involved between industry water users and the historically disenfranchised Tribal communities, resulting in water extraction and uses that further risk the ability

[103] Lewis, J. et al. (2017).

[104] Tanana, H., et al. (2021)

[105] Ibid.

[106] Congressional Research Services. (2011). Indian Reserved Water Rights Under the *Winters* Doctrine: An Overview. Reports to Congress RL32198. https://crsreports.congress.gov

[107] Congressional Research Services. (2022). Indian Water Rights Settlements. Report to Congress R44148. https://crsreports.congress.gov/product/pdf/R/R44148

[108] USBR (2018)

[109] USBR (2018); Walton, B. (2015, July 1). *In Drying Colorado River Basin, Indian Tribes Are Water Dealmakers*. Circle of Blue - WaterNews. https://www.circleofblue.org/2015/world/in-drying-colorado-river-basin-indian-tribes-are-water-dealmakers/

[110] Baltz, T. (2020, June 17). *Navajo, Battling Covid, Say Coal Mines Sapped Drinking Water*. Bloomberg Law. Retrieved September 30, 2022, from https://news.bloomberglaw.com/environment-and-energy/virus-ravaged-navajo-say-coal-mines-sapped-their-drinking-water

[111] Ibid.

[112] Ibid.

of those communities to be resilient under the drought conditions exacerbated by climate change. In essence, it is a prime example of the climate change - water injustice cycle.

While this case is illustrative of the conditions of water justice in the CRB, and thus presents opportunities for where to focus data science, it is vital to consult the stakeholders' themselves about their priorities with regard to these water justice issues. There have been numerous reports by key Tribal actors and partnerships that outline these needs, both in addressing climate change generally and water issues specifically. These are the areas explored in the final sections of this paper to see where there are alignments between data science and community-expressed areas of importance.[113]

Section II: Data Science Engagement - A Scalar Framework

For data science to engage with water justice challenges, it must consider the scale and context in which the challenge is operating, articulate the justice goal being centered, and apply a justice-oriented lens to understanding the data landscape involved. Following this trajectory will allow data science to identify the specific, contextual ways in which it can best be applied to serve water justice. It is important to distinguish that there are two underlying concepts in this space - using data science *for* justice and fostering justice *within* data science practice. This section and the recommendations in Section IV focus on the former, but the latter is a vital part of moving water resources into a more equitable future for all and is discussed briefly in the Appendix. There is another caveat as well - this framework presents a path to align the data science engagement process with a given water justice challenge, using the CRB and Tribal communities as a case study, but it does not represent every element that should possibly be considered. In this way, it is the very beginning of the work, not the end.

Scales of Engagement

Because drought and justice in the CRB is such a vast issue with a myriad of stakeholders, it is a data rich environment that can provide multiple avenues of data science engagement. However, it is also an uncoordinated data environment and significant gaps exist, particularly for Tribal communities.[114] The amount of data is also challenging to analyze as it is generated across so many different actors and lacks standardization,[115] an issue felt across water-use data in the U.S. and many other environmental management fields where data systems lack broadly accessible and usable qualities.[116] While this is a critical underlying

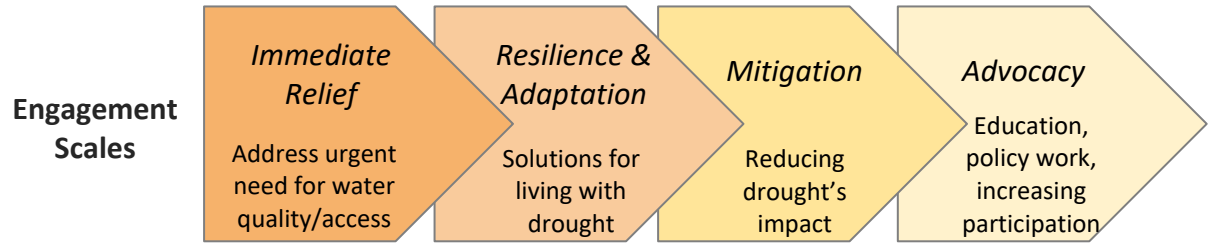
[113] E.g., see information provided by USBR (2018); Tanana, H. et al. (2021); Native Nations Climate Adaptation Program (2017) Southwest Tribal Climate Change Assessment Final Report.University of Arizona. https://www.nncap.arizona.edu/projects/2017-Southwest-Tribal-Climate-Change-Assessment; Frus, R.J., Hawbaker, T. J., Anderson, E.D., Anderson, P.J., Andrews, W.J., Bradford, J.B., Dean, D.J., Duniway, M.C., Horton, R.J., Jones, D.K., Monroe, A.P., Qi, S.L., Skinner, C., Thomas, K.A., Tillery, A.C., Torregrosa, A., and Dahm, K.G., 2021, A snapshot of stakeholder science needs related to drought in the Colorado River Basin: U.S. Geological Survey Data Release, https://doi.org/10.5066/P9CTXP26

[114] USBR (2018)

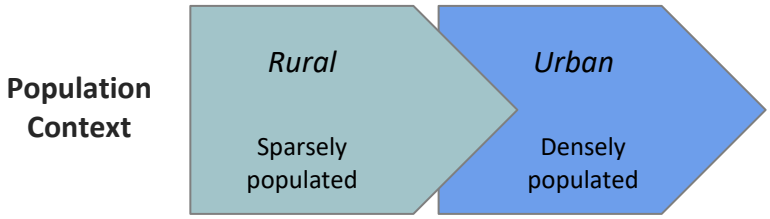
[115] https://waterdesk.org/2020/10/colorado-river-data-management/; Sternleib, F. Babbitt Center for Land and Water Policy (personal communication, Sep 16, 2022) also confirmed the disparate nature of water data in the basin

[116] Cantor, A., Kiparsky, M., Hubbard, S. S., Kennedy, R., Pecharroman, L. C., Guivetchi, K., Darling, G., McCready, C. & Bales, R. (2021). Making a water data system responsive to information needs of decision makers. *Frontiers in Climate*. https://doi.org/10.3389/fclim.2021.761444; Dosemagen, S., & Williams, E. (2022). Data Usability: The Forgotten Segment of Environmental Data Workflows. *Frontiers in Climate*, *4*, 785269. https://www.frontiersin.org/articles/10.3389/fclim.2022.785269/pdf; Marston, L. T., Abdallah, A. M., Bagstad, K. J., Dickson, K., Glynn, P.,

challenge, one way to find data science engagement points amidst this structural issue is to start with narrowing the data science focus based on the scale of the particular problem/solution area. Water justice challenges, both globally and specifically for the context of Tribes in the CRB, appear along a continuum of impact scales - from acute issues like immediate threats to water access, to chronic challenges such as fostering adaptive agriculture management under drought. Accordingly, data science solutions can look to address these challenges by utilizing a scalar framework, targeting either one or multiple scales.



In addition, it is important to consider the human population context at which solutions will operate, as this context frames specific issues even further as well as the type of solutions that will be feasible. This framework will use the broadest scale of rural to urban populations, as more specific issues and stakeholders will be identified in the final element of the framework. Additional stakeholders for which justice is being centered should be added when applying the framework to a given issue (i.e., rural tribe populations, rural hispanic populations). Using this continuum allows for this framework to be used in other contexts, but the examples provided in the final section of this landscape will focus on rural contexts as that is where many of Tribes in the CRB live.[117]



As an example of utilizing these scale and context elements, if focusing on immediate relief in a rural population context, one data science solution might be mapping rural water access to prioritize where to send water relief under drought conditions. When targeting resilience and adaptation in urban contexts, another data science example is analyzing water use data to predict demand, providing insights for better water management - a strategy used by DataKind in the past with the Moulton Niguel Water District.[118] Yet, as this paper has discussed, applying data science to a particular problem in the Colorado River Basin is not enough to truly move the needle on water justice.

Larsen, S. G., Melton, F.S., Painter, J.A., Prairie, J., Ruddell, B.J., Rushforth, R.R., Senay, G.B., & Shaffer, K. (2022). Water-Use Data in the United States: Challenges and Future Directions. *JAWRA Journal of the American Water Resources Association*.

[117] Tanana, H., et al. (2021)

[118] DataKind. (n.d.). *Forecasting Water Demand in California When Every Drop Counts*. Retrieved August 2, 2022, from https://www.datakind.org/projects/forecasting-water-demand-in-california-when-every-drop-counts

Centering Water Justice Goals

After identifying a primary scale and context at which to operate, it is important that any approach pays attention to the issues of justice that the cycle of climate change and historic social inequalities fosters in the basin. Data science in general can fall prey to abstraction that ignores these realities and perpetuates them, resulting in growing calls from the data science and social justice communities to more intentionally address data science's role in these dynamics.[119] The first step in this shift is to make explicit that water has a physical, ecological, social, and historical reality that needs to be accommodated by instead of abstracted from solutions.[120] As Anson and her colleagues point out - "Water itself is computed as a data currency, treated as an abstracted commodity or financial future in water financialization systems, far from its reality as a natural resource and ecology."[121] And so, one of the next steps for ensuring that a data science approach reflects waters' complex qualities and social realities is to articulate a specific justice goal to work towards, making it clear that it is not working toward an objective solution but one rooted in acknowledging the foundation of injustices so many of these problems have. The framework presented here operationalizes this step by mapping onto the pillars of water equity by US Water Alliance.[122] These goals generally fall into a similar frame as the engagement scales, as shown in the final table below. To be clear, these are not the only justice goals that can be centered but represent one broad approach in order to develop the framework. Once a particular stakeholder group (or groups) is identified for a given water justice issue, these goals can (and should) be replaced with more context specific ones.

US Water Alliance Water Equity Goals

+ Have access to safe, clean, affordable drinking water and wastewater services;
+ Share in the economic, social, and environmental benefits of water systems; and
+ Are resilient in the face of floods, drought, and other climate risks

[119] Gutierrez, M., & Bryant, J. (2022); Green, B. (2021). Data science as political action: Grounding data science in a politics of justice. *Journal of Social Computing*, *2*(3), 249-265. https://doi.org/10.23919/JSC.2021.0029

[120] Anson, A., Ballestero, A., Chahim, D., CIEJ, Dryer, T., Gerson,S., Henry, M., Hobart, H. J., Hoover, F. , Roane,J.T.,Salomón, A., Seraphin,B., & Sobrino,E. (2022). Water Justice and Technology: The COVID-19 Crisis, Computational Resource Control, and Water Relief Policy. AI Now Institute at New York University, January 10, 2022, https://ainowinstitute.org/water-justice-technology.html. Hereafter Anson, A., et al. (2022); Doorn, N. (2021). Artificial intelligence in the water domain: Opportunities for responsible use. *Science of the Total Environment*, *755*, 142561. https://doi.org/10.1016/j.scitotenv.2020.142561

[121] Anson, A., et al. (2022). Pg. 19

[122] U.S. Water Alliance. (n.d.). *The Pillars of Water Equity*. Water Equity Clearinghouse. Retrieved October 4, 2022, from http://uswateralliance.org/wec/framework

Applying a Justice Lens to Focus Efforts

In addition to articulating specific justice-centered goals to work towards, a given data science approach must critically reflect on the data landscape in which it hopes to operate, paying attention to the ways data has been created, analyzed, and used and how this process has affected the creation or amelioration of water injustices in a given context. This step requires attunement to local contexts, knowledge, and stakeholders, a reflection of the growing calls for a community-driven approach to data-based solutions from White House Environmental Justice Council[123] to scholars[124] to practitioners. The framework presented here defines this process as applying a justice lens to a data science approach, and entails asking questions about a given "typical" data science approach in order to further focus the work into a space that is centering justice. The answers to the questions will highlight potential inequalities in the development or application of a strategy, which then serves as a vital entry point to address.

Justice Lens Questions

- Data Availability - What data is available, who created it, and what/who is it overlooking?
- Data Users - Who has access to and can use data?
- Data Application - How is the data being used to make decisions? Who is making the decisions? Who is left out?

In essence, these questions are aimed at embodying the definition of water justice provided earlier. As such, applying this lens works to help a data science approach engage in this critical exploration in order to advance solutions that can meaningfully foster water justice, reflecting specific contexts in which it is created:

> *The interactive societal and academic endeavor to critically explore* ***water knowledge production [data availability], allocation [data users] and governance [data application]*** *and to combine struggles against water-based forms of material dispossession, cultural discrimination, political exclusion and ecological destruction, as rooted in* ***particular contexts***.[125] [emphasis added]

[123] Martin, C. (2021). The landscape of data capacity in U.S. environmental justice organizations. The Urban Institute. https://www.urban.org/research/publication/landscape-data-capacity-us-environmental-justice-organizations

[124] Doorn, N. (2021). Artificial intelligence in the water domain: Opportunities for responsible use. *Science of the Total Environment*, *755*, 142561. https://doi.org/10.1016/j.scitotenv.2020.142561

[125] Mills-Novoa, M., et al. (2022). p.404

Putting It All Together

The table below represents an overview of potential engagement areas for data science in the CRB, using the combined elements of the scalar framework discussed above, but does not yet apply the justice lens questions. After a review of the key actors working against the problem, agenda setters, and funders, an additional table of recommendations mapping this framework onto the Colorado River Basin is provided in the final section of the paper, finalizing this schema.

Engagement Scale	**Water Justice Goal**	**Population Context**	**Examples of Typical Data Scienceable Approach**	**Justice Lens Focusing Questions** Data availability, Data Users, Data Application
Immediate Action Addressing acute water security challenges	Have access to safe, clean, affordable drinking water and wastewater services	Rural	Mapping water security risk - water access and quality Identifying water infrastructure needs	To be applied in Section IV
		Urban	Mapping utilities connections and find associated risk factors for disconnection	
Resilience & Adaptation Strategies for living under drought conditions	Are resilient in the face of floods, drought, and other climate risks	Rural	Model agricultural water banking to determine economic feasibility Predicting drought risks	
		Urban	Predicting water demand for different users for adaptive management	
Mitigation Reducing impact of drought	Are resilient in the face of floods, drought, and other climate risks	Rural	Identifying natural infrastructure to restore for water resource protection	
		Urban	Municipal reuse and conservation analysis and/or monitoring	
Advocacy Education, research and policy work to increase participation and justice	Share in the economic, social, and environmental benefits of water systems	Rural	Citizen science to improve gaps in water access data	
		Urban	Creating dashboards of water use for increasing water use awareness	

Section III: Review of Current Efforts in the Colorado River Basin

With a framework for data science and water justice in the CRB established, this section reviews the key categories of actors already working in this space, providing a foundation from which to answer the justice lens questions of the framework in Section IV. There are four main categories of actors covered - non-governmental, governmental, academic/research based, and funders. This amalgam utilizes strategies from direct service to basin wide funding and decision-making, collectively setting the agenda of the current efforts to address drought and/or water justice in the region.

Non-Governmental Actors

Given the pressing and urgent needs of addressing drought and fostering water justice therein throughout the Colorado River Basin, there has been a surge of activity directed toward this challenge in recent decades. The discussion in this first section is focused on primarily non-government actors that are tackling the issue from a direct-service approach - providing vital response, adaptation, and mitigation resources to those most affected by the drought - particularly those paying attention to issues of justice. That said, there are few organizations that focus primarily on water justice in the CRB, with most operating at broader scales, looking to address drought and the dwindling CRB from a water allocation and supply approach generally. The main categories of work are mapped onto the scales of engagement provided in Section II - immediate aid for water security (e.g., providing water access, addressing quality), fostering resilient management and adaptation (e.g., smart technologies, data for decision-making), mitigation solutions (e.g., ecosystem restoration), and advocacy work (e.g., legal support, education, collaboration). Actors might work in more than one or all of these categories, but the table below organizes them based on where the majority of their efforts lie. The types of actors range from small, local non-profits to large multi-state organizations with substantial funding. The below table and the ones in subsequent sections are by no means exhaustive but represent a large sample of the dominant actors involved.

Organization	Scale/Target Stakeholders	Approach
Immediate Aid for Water Security (Access, Quality, Infrastructure, Maintenance)		
DigDeep	U.S., with specific Navajo Nation projects	Provide indoor water plumbing access in the Navajo Nation:
St. Bonaventure Indian Mission and School	Navajo Nation	Water hauling partner with DigDeep support, provides water to Eastern Navajo Nation
Navajo Nation COVID-19 Water Access Coordination Group (WACG)	Navajo Nation	Focused on increasing access to safe, reliable water in the Navajo Nation
RCAC	Western U.S., with rural Tribe programs	Safe water access, capacity building, loans for infrastructure

Community Water Center	California	Direct service and community resources for safe water access, coalition building, policy advocacy Drinking Water tool
Resilient Management/Adaptation - Living with Drought's Impacts (smart tech, water use management, ag innovation, etc.)		
New Mexico Water Data	New Mexico	Open water data platform for NM Water management
SERI	Arizona	Research and solutions targeting environmental justice issues in Tucson + Financial and technical support for rain harvesting for limited-income families
Colorado Water Trust	Colorado	Colorado River restoration + myRiverBalance program: + Economic approach - donate money to balance household water use, money used to buy or lease water for conservation + Improving infrastructure projects + Water rights - Request for Water Acquisitions Process
Open Water Foundation	CRB	Provide open data and software for water management
OpenET	Western US	Provides satellite-based data to estimate consumptive use for agriculture
Internet of Water Coalition	U.S., with CRB specific projects	Working to modernize water data infrastructure via affordable, open source tech for sharing data towards better water management
One Water Solutions Institute	Global, but CRB specialty	Software solutions to improve water systems management, e.g., eRAMS platform
The Nature Conservancy	U.S., with CRB specific projects	Agricultural Water Banking - market based system of water allocation to compensate users for reducing consumption Agriculture efficiency support - crop switching to more efficient plants/irrigation methods Infrastructure improvements Partnerships
Environmental Defense Fund	US, with Western programs	Western Water Program + Conserving water in Lake Mead + Smart Ag to restore supply + Support for Open Evapotranspiration Data Platform
Mitigation Solutions - Reducing Droughts Effect by Reducing Demand/Fostering Supply (ecosystem restoration, water conservation/reuse, etc.)		
Local water utilities (e.g., Denver Water)	CRB	Urban water conservation efforts and integrating climate change into planning for sustainable water supplies. Examples here and here. -
RiversEdge West	Western US	River restoration, invasive removal
Center for Snow and Avalanche Studies	Western US	Dust on snow and other snowfall management data
Sonoran Institute	Western US	River restoration, community-based conservation

Trout Unlimited	US, with Western programs	Western Water and Habitat Program - Emphasis on partnership building to accomplish habitat protection, restoration, and reconnecting fragmented habitats
American Rivers	U.S., with CRB specific projects	Policy support/lobbying for river restoration projects
National Audubon Society	U.S., with CRB specific programs	Conservation policy advocacy, education, and support for conservation projects in the CRB
Theodore Roosevelt Conservation Partnership	National	Water conservation policy advocacy and conservation/restoration projects
Advocacy Work (education, legal, funding, policy etc.)		
Ten Tribes Partnership	CRB Tribes	Advocacy for Tribal community sovereignty, river stewardship, and decision making in the CRB
Water and Tribes Initiative	CRB Tribes	Collaborative stakeholder engagement and decision making Research on Tribal issues, particularly related to water
Tribal Water Center	U.S. Tribes	Resource for Tribes - education, planning tools, capacity building
Colorado River Water Users Association	CRB	Forum and resource for stakeholder discussion and collaboration around Colorado River water resources
Western Resource Advocates	Western US, Colorado River specific projects	Political advocacy, research, and financial support for solutions that support healthy rivers, climate etc, with CRB specific projects.
Water for Colorado	Colorado	Support securing funding for projects to enact the Colorado Water Plan
West Big Data Innovation Hub	U.S., with a Western chapter	Advocating for big data sharing and collaboration
Resilient West	Western US	Joint program of Sonoran Institute and Babbitt Center that provides community assistance (technical assistance, resources, training) to support resilience under climate change
Bonneville Environmental Foundation	National	Multiple programs that target corporate water advocacy and funding for conservation projects + Change the Course: Program for water project sponsorship + Business for Water Stewardship: Business voice for water stewardship - represents major companies and supports policies, advocates for funding projects
US Water Alliance	National	Water issue advocacy networking group, focused on policy work and fostering water management solutions + One Water Hub + Water Equity Initiatives
Water Education Foundation	National	Resources, collaboration on water resources
River Network	National	River advocacy work, moving towards more collaboration with Tribes

Academia and Research Centers

Another key area of work being done is that of the larger academic community and research centers. While in some ways these actors are working directly against the problem through practice-oriented research and application (e.g., extension departments), they also set the agenda by defining the kinds of research being prioritized, and thus the kind of information and data that are produced and used by other actors. The following table is a summary of the academic and research centers that are involved in water justice and related issues within the Colorado River Basin. Because these actors and their research tends to cut across a wide variety of approaches to the issue, their work is summarized versus aligned with the engagement scales.

Institution	Scale/Target Stakeholders	Approach
Universities		
University of Arizona *Indigenous Resilience Center*	Global Indigenous Communities, US focus	Indigenous resilience research, education, and outreach
University of Arizona *Native Nations Institute*	US Native Nations	Fostering Native Nation building and governance
University of Arizona *Center for Climate Adaptation Science and Solutions*	US, with Tribal and Native Nations programs	Tribal Resilience and Adaptation Theme - focuses research on tribal responses to climate change Native Nations Climate Adaptation Program - provides reports, analysis, climate adaptation tools, networking
Northern Arizona University *Institute for Tribal Environmental Professionals*	US Native Nations	Increasing tribal capacity and sovereignty to manage environmental and natural resources National Tribal Water Council - technical group that works to collaborate between EPA and tribes on water issues. Provide priority reports:
University of New Mexico *Water Resources Program*	SW region	Water issue research focused on equity and sustainable use Native American Water Rights Settlement Project - documents Native water rights in the US
Utah State University *Colorado River Research Group*	CRB	Specific scholarship focus on understanding the dynamics of the CRB, with emphasis on facilitating sustainable governance and management:
Colorado State University *Center for Environmental Justice*	Global, with CRB specific research	Research on Environmental Justice in the Rio Grande
Colorado State University *Colorado Water Center*	Global, with Colorado and CRB specific projects	Leads research on water issues in Colorado and beyond, is also a Water Resources Research Institute (USGS designation)
University of Colorado Boulder *Western Water Assessment*	Western US	Substantial producer of research/data access on water issues in intermountain range and CRB specifically

University of Colorado Boulder *Colorado Law Native Communities and Environmental Justice Program*	Western US	Research and legal assistance for acequia irrigation and water rights, intertribal salmon treaty, and created a database on climate change adaptation resources
University of California Berkeley *The Berkeley Water Center*	Global water research	Equity and Environmental Justice work within water center:
Johns Hopkins University *Center for American Indian Health (JHCAIH)*	US Native communities	Study water security impacts on health in Navajo Nation and COVID-19 and water resources
Think Tanks and Research Centers		
Babbitt Center for Land and Water Policy, a center of the Lincoln Institute of Land Policy	US, with projects focusing on CRB	Research, community training, partnership building around water and land management in the basin: + Small city water data hub + Growing Water Smart integrated planning workshops + Open GIS Data Portal for the CRB
Pacific Institute	Global, with US emphasis	Think tank, research and policy work on water resources
Desert Resources Institute	US	Non-profit research arm of Nevada Higher Ed, provides substantial water research and data
CUAHSI	US	Platform for sharing water science data and resources
RAND	Global, US focus	Climate resilience research center with previous work on Colorado River Basin assessments
World Resources Institute	Global	Water Program emphasizes data and analysis tools for decision making:

Government Actors

In addition to the work described above, there are a plethora of entities at every level of governance - local, state, regional, national, and Tribal - that are involved in setting the core agenda and direction of solutions in the Colorado River Basin. However, the bulk of decision-making, data generation, and funding flows from the top down because the CRB is a transboundary resource, allocated and managed at a federal level, and the federal government has the trust responsibility to ensure the protection, well-being, and sovereignty of Tribes. As such, this section focuses on government actors at a national and regional level, summarizing their core approaches and activity areas as they relate to drought, water management, and/or justice in the Colorado River Basin, particularly for Tribal communities. In addition to these activities, these government actors are also the main source of funding for all things related to water in the basin, as well as key players in addressing immediate water security issues (e.g., infrastructure support, water pollution, water access, etc.). Although, as pointed out

in Section II, the government often does not fulfill its obligation to properly fund and support water access for Tribal communities.[126]

Even though this section won't detail the numerous state and local level government actors, it is nonetheless important to point out their vital role. Every state has its own water governance bodies (e.g., watershed management districts, conservation districts, water boards, irrigation districts), which are responsible for the specific issues and management of water within their boundaries. States also help create basin-wide drought contingency plans submitted to the Bureau of Reclamation, which outline specific strategies to respond to drought in a way that allows the allocations of the 1922 Colorado River Compact to be upheld.[127] In addition, Tribal governments are particularly key in developing targeted drought responses and relevant data science solutions, but as with each of the seven states of the basin, each of Tribes have their own governmental structure and authority agencies. Strategies at this scale of governance abound; for example the Central Arizona Project has supported the development of N-drip irrigation for Colorado River Indian Tribes.[128] These smaller-scale actors and their work are critical to the implementation of decisions and distribution of funding and resources that address drought and water justice in the CRB. It is important to thoroughly engage with these actors when exploring a specific data science approach in this arena to ensure they fit the targeted stakeholders' needs and that efforts are not duplicated, but to enumerate them here would detract from the broader data science platform being developed for this landscape.

Organization	**Approach** (Water, Drought, Justice Related)
US Department of the Interior *Bureau of Reclamation (BOR)*	Key programs - SECURE Water Act, the WaterSMART program, and Basin Studies across the West + Primary source of water use data in the CRB + Summary of work addressing drought in West Substantial funder and project support for water management issues in the CRB
US Department of the Interior *Bureau of Indian Affairs (BIA)*	Tribal Climate Resilience Center + Working to support preparation/resilience in the face of climate change for Tribes + Dashboard Map of Indigenous Peoples Resilience Actions + Tribal Climate Resilience Liaisons to connect networks of tribes to resources within Dept of Interior Division of Water and Power + Management of water resources owned by BIA + Branch of Water Resources focuses on water rights and water management support Funding to support water infrastructure and other Tribal needs generally (E.g., Hopi Arsenic Mitigation Project)
U.S. Geological Survey (USGS)	Vital source of public data on water use and availability

[126] Tanana, H., et al. (2021)

[127] NIDIS/NASA. (2019, February 12). *Colorado River Drought Contingency Planning*. Drought.Gov. https://www.drought.gov/news/colorado-river-drought-contingency-planning

[128] Richardson, M. (2021, November 19). *Innovative Irrigation System Aims to Save Dwindling AZ Water Supplies*. Public News Service.https://www.publicnewsservice.org/2021-11-19/water/innovative-irrigation-system-aims-to-save-dwindling-az-water-supplies/a76619-1

	+ National Data + Dashboards for visualizing and basic analysis + Water Resource Research Institutes + CRB specific work: - Moving towards more complex data, machine learning, and linkages - Stakeholder science needs in the basin Tribal projects via Climate Adaptation Science Center (CASC) + SW CASC: Projects Lists, and collaboration with University of Arizona
U.S. National Oceanic and Atmospheric Administration (NOAA)	Key provider of climate and drought analysis/reports/forecasts for the CRB Partner in the National Integrated Drought Information System
U.S. Environmental Protection Agency (EPA)	Drinking water quality data Water conservation education and monitoring (WaterSense) EPA role for Tribes + Enforcing Clean Water Act, Safe Drinking Water Act and supporting Tribal access to safe water + Infrastructure Taskforce
U.S. Department of Agriculture (USDA)	Provides agriculture related data, including self-reported irrigation information and data for the U.S. Drought Monitor
U.S. Army Corps of Engineers	Institute of Water Resources: Data and analysis tools for civil works projects Engineering with Nature: No current CRB projects, but potential future work; Aligning of natural and engineering processes
NASA	EarthData Resources: Open source, remote sensing based data for water use Western Water Applications Office: Partnering NASA data with water managers to manage water in the west
Western States Water Council - government entity, formed by states governors, 18 states, including CRB	Water Data Exchange (WaDE) program: working to share and streamline data collection, management, and use for decision-making + Research and assessment of water use data and capabilities in the region + Western States Water Data Access and Analysis Tool (WestDAAT) being developed + Maps of water rights
Upper Colorado River Commission	Ensure the appropriate allocation of water in Upper Basin and compliance with the 1922 Colorado River Compact + Assists with stream gauging, forecasting, rules and regs, data analysis and reporting

Funders

In addition to the government entities described in the previous section, who collectively provide a substantial, if not majority, portion of funding for the overall management of the CRB, there are several crucial philanthropic and corporate funders that support projects in water management, drought, and climate change in the CRB. It is important to note, however, that outside of the government funding programs, very few entities focus on

specific water justice challenges for Tribal communities, instead focusing on broader initiatives for overall CRB drought related issues.

Organization	Focus Areas
Philanthropic	
Walton Family Foundation	The largest private funder of initiatives in the basin Emphasis is on demand management, but also funds numerous non-profits, research, etc. that cover everything from invasive removal to reporting (i.e., funds the Water Desk)
Kresge Foundation	Equitable solutions for climate-related water issues in urban areas
Water Funder Initiative	Network of water-focused funding partners
Gordon and Betty Moore Foundation	Environmental Conservation projects, e.g., supports the National Fish and Wildlife Foundation's Fisheries Innovation Fund
Pisces Foundation	Emphasis on "One Water" management and integrated approaches/data
National Fish and Wildlife Foundation	Conservation and restoration focused projects in the basin
Udall Foundation	Funds leadership, education and conflict resolution related to natural resources and Native nations
Conservation Fund	Land and water conservation projects
Water Foundation	Watershed and community focused projects
Gates Family Foundation	Colorado specific, focus areas include educational equity, natural resources, community development, and informed communities
Mighty Arrow	Land and Water systems, current projects funded in Colorado to support conservation
The Funders Network	Education and advocacy for funders to align on issue areas, e.g., Urban Water Program
Quantified Ventures	Funding initiative to support solutions for water scarcity in CRB
Corporate	
Intel	Substantial river flow restoration projects in the CRB with various partner orgs, particular emphasis on Arizona water
Danone North America	Silk brand became first sponsor of Change the Course program by Bonneville Environmental Fund
Anheuser-Busch Foundation	Provided $1.8 million to Nature Conservancy projects that focus on river restoration and quality:
PepsiCo Foundation	Funding projects in the CRB related to conservation and restoration + Funds projects with The Nature Conservancy + Colorado River Basin Fund

Section IV: Recommendations for DataKind and Water Justice

So where does DataKind fit into this large and complex landscape? In general, the objective for DataKind is to move it towards fostering justice in the CRB by responding to the growing calls from scholars and practitioners to tap into existing water justice knowledge and needs within this space, being careful to avoid the pitfalls of big data analysis that have historically overlooked or even contributed to injustice,[129] as discussed in Section II. Therefore, since data is rich in the CRB, albeit chaotic, and engagement with local actors is critical to both water justice and DataKind's mission, DataKind can look to the work of existing actors to elevate and support their efforts as a primary approach. This echoes trends in the general data science field to work towards community-based knowledge, locally-centered solutions and increasing community capacity for monitoring, analysis, and response.[130] The first part of this recommendation will summarize key actors to explore engaging with to gain a better sense of the landscape. The second half will fulfill the scalar framework provided in Section II to highlight specific examples of data science for water justice opportunities in the CRB for Tribes specifically.

Actors to Engage for Issue Orientation

The first place to start exploring areas for engagement should be at the federal level since the federal government is largely responsible for the data, funding and decisions of water and drought response in the CRB, in addition to being the trust responsibility of the Tribes. This scale of exploration also provides an initial orientation to the data that are often used by other actors. Such an approach might look like engaging with the vast resources and projects of the USGS, who is moving towards developing more collaborative approaches to water data.[131] As a key agenda setter and data producer both nationally and in the CRB, they are attuned to the specific data science gaps and analysis needs in the region. Indeed, a recent stakeholder survey project produced a detailed list of CRB stakeholders and their needs, which ultimately served to highlight specific examples of potential data science engagement opportunities in the table below.[132]

Narrowing in on regional government level actors, another touchpoint is the Western States Water Council. This group of governor-appointed representatives from 18 western states created in 1965 works to coordinate conservation, development, and management of water in the region.[133] In addition to many collaborative functions, it also maintains the Water Data Exchange Program (WaDE), a repository of water data in the region

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[129] Gutierrez, M., & Bryant, J. (2022). The Fading Gloss of Data Science: Towards an Agenda that Faces the Challenges of Big Data for Development and Humanitarian Action. *Development*, *65*(1), 80-93.

[130] Anson, A., Ballestero, A., Chahim, D., CIEJ, Dryer, T., Gerson,S., Henry, M., Hobart, H. J., Hoover, F. , Roane, J.T.,Salomón, A., Seraphin,B., & Sobrino,E. (2022). Water Justice and Technology: The COVID-19 Crisis, Computational Resource Control, and Water Relief Policy. AI Now Institute at
New York University, January 10, 2022, https://ainowinstitute.org/water-justice-technology.html; Martin, C. (2021). The landscape of data capacity in U.S. environmental justice organizations. The Urban Institute. https://www.urban.org/research/publication/landscape-data-capacity-us-environmental-justice-organizations

[131] Read, J. S. (2021, March 5). Water Data Science in 2021. *Water Data for The Nation Blog*. https://waterdata.usgs.gov/blog/water-data-science-2021/

[132] Frus, R.J., Hawbaker, T. J., Anderson, E.D., Anderson, P.J., Andrews, W.J., Bradford, J.B., Dean, D.J., Duniway, M.C., Horton, R.J., Jones, D.K., Monroe, A.P., Qi, S.L., Skinner, C., Thomas, K.A., Tillery, A.C., Torregrosa, A., and Dahm, K.G., 2021, A snapshot of stakeholder science needs related to drought in the Colorado River Basin: U.S. Geological Survey Data Release, https://doi.org/10.5066/P9CTXP26. Hereafter Frus, R.J., et al. (2021).

[133] *What is the Western States Water Council?* (n.d.). About WSWC. Retrieved October 4, 2022, from https://westernstateswater.org/about/

to help streamline water access, rights, and use data for better management across entities.[134] A dashboard that allows for analysis, Western States Water Data Access and Analysis Tool (WestDAAT), is planned to launch Fall 2022.[135] In 2014, the council also engaged in a state-wide water data collection and management capabilities assessment[136], which highlights key trends and challenges in water data in the region, and thus areas that data science could enter. Starting with these large-scale government actors would be just the beginning of data science engagement, as truly understanding how data science can meaningfully affect water justice entails working at a more local scale with those directly impacted.

Data Science for Water Justice Opportunities to Explore

As the Tribes of the CRB are the focus of the water justice explorations in this landscape, it is vital to narrow in on the specific ways that data can be used to support the work being done to address the current water injustices they face. The following table finalizes the scalar framework provided in Section II and uses the information on the current status of work in the CRB to answer the justice lens questions and identify specific areas that DataKind can initially explore. To reiterate, the core justice lens questions are:

- Data Availability - What data is available, who created it, and what/who is it overlooking?
- Data Users - Who has access to and can use data?
- Data Application - How is the data being used to make decisions? Who is making the decisions? Who is left out?

The examples below highlight four key data science approaches that emerged time and again in the review of existing work and reports in this landscape as priorities for Tribes in the CRB.[137] These four examples help illustrate how to use the data science for water justice scalar framework, but additional examples are provided in narrative form after the table. Across all examples, a key data trend is that what data is available is generally not reflective of current conditions or local-level specificity for Tribes, necessary features for adaptive management and accurate response to drought and other water justice issues. It is also important to note that initiating any collaboration with a Tribal community should follow established best practices.[138]

[134] Western States Water Council. (n.d.). *Water Data Exchange (WaDE) Program*. Retrieved September 10, 2022, from https://westernstateswater.org/wade/

[135] Western States Water Council. (n.d.). *WaDE Dashboard: Prototype*. Retrieved September 10, 2022, from https://westernstateswater.org/wade-dashboard/

[136] Western States Water Council. (2014). *Western State Water Program Capabilities Assessment Survey and Report*. https://www.westernstateswater.org/wp-content/uploads/2014/06/Western-State-Water-Program-Capabilities-Assessment-Survey-Report-FINAL-June2014.pdf

[137] Note, this assessment is based on reports like USBR (2018), Tanana H. et al (2021) and Frus, R.J., et al. (2021) among others, but it is crucial to speak with leaders in a given community to understand their specific needs

[138] Climate Science Alliance. (n.d.). *Building Authentic Collaborations with Tribal Communities: A Living Reference for Climate Practitioners*. Meaningful Engagement. Retrieved September 28, 2022, from https://www.climatesciencealliance.org/info/meaningful-engagement

Engagement Scale	Population Context	Water Justice Goal	Typical Data Scienceable Approach	Justice Lens Focusing Questions Data availability, Data Users, Data Application	Specific Strategy to Explore
Immediate Action Addressing acute water security challenges	Rural CRB Tribes	Have access to safe, clean, affordable drinking water and wastewater services	Mapping water security risks - drinking water access and quality	**Data availability** - sporadic data, lacking timeliness and community level specificity, challenging to access + Some drinking water facilities/infrastructure for Tribes mapped by EPA (SDWIS)[139] + Indian Health Services (IHS) reports on deficiencies in sanitation services for Tribes[140] + US Census American Community Surveys, questions on household access to plumbing[141] **Data users** - Generally Federal and State, some data is public **Data application** - EPA uses data to determine Clean Water Act/Safe Drinking Water Act compliance and assistance needs, IHS uses reports to prioritizing sanitation project spending, US Census surveys used for a variety of projects	Work with local organizations (e.g., Water and Tribes Initiative) to develop tools to map household level water access and use, contributing to identified need for finer scale water use and supply data in Tribal communities[142] Work with Hopi Tribe to identify sources of water contamination, contributing to remediation of known problems with arsenic contamination from previous mining operations[143]
Resilience and Adaptation Strategies for living under drought conditions	Rural CRB Tribes	Are resilient in the face of floods, drought, and other climate risks	Predicting drought	**Data availability** - U.S. Drought Monitor, made with	Work with Tribal Departments of Nature Resources/Water Resources/etc. to develop local level tools for predicting drought (see examples from Hopi and

[139] Safe Drinking Water Information System: https://www.epa.gov/enviro/sdwis-search-indian-tribes

[140] Indian Health Services. (2019). *Annual Report To the Congress of the United States On Sanitation Deficiency Levels for Indian Homes and Communities—Fiscal Year 2019*. https://www.ihs.gov/sites/newsroom/themes/responsive2017/display_objects/documents/FY_2019_RTC_Sanitation_Deficiencies_Report.pdf

[141] U.S. Census Bureau, 2016-2020 American Community Survey 5-Year Estimates. DPO4 - Selected Housing Characteristics. https://data.census.gov/cedsci/table?tid=ACSDP5Y2020.DP04.

[142] USBR (2018), see Table 9-A

[143] Tanana, H., Combs, J., & Hoss, A. (2021). Water is life: law, systemic racism, and water security in Indian Country. *Health security*, *19*(S1), S-78; Frus, R.J., et al. (2021).

				data from USDA and NOAA[144], lacks local level specificity **Data users**- Federal, State and Tribal **Data application** - Triggers federal relief mechanisms like low interest loans, farm relief, etc. made at a federal and state level, does not always reflect needs of local Tribal communities	Navajo Nation partnerships[145])
Mitigation Reducing impact of drought	Rural CRB Tribes	Are resilient in the face of floods, drought, and other climate risks	Identifying natural infrastructure to protect/restore for water resource resilience	**Data availability** - USGS/NASA Landsat and other remote sensing data[146], broadly accessible but requires advanced skills for analysis **Data users** - Federal and State agencies, general public and research communities **Data application** - wide ranging, but technical expertise required for analysis means it is often not used by Tribes	Analyze satellite imagery in conjunction with tribal values and priorities to identify riparian restoration plans (see example from the SW CASC project of riparian mapping of San Carlos Apache Reservation and Upper Gila River Watershed[147])
Advocacy Education, research and policy work to increase participation and justice	Rural CRB Tribes	Share in the economic, social, and environmental benefits of water systems	Quantify/map historic water rights for Tribes; create hydrological dashboards for ease of access and analysis	**Data availability** - scattered and a mix of digital, written, and analog water rights records. Large source of data is the Bureau of Reclamation. Consolidated information can be found by third parties[148] **Data users** - primarily Bureau of Reclamation and Tribes **Data application** - managing water resources, establishing long held precedent rights to water	Work with Western States Water Council to assist in mapping/analyzing water rights,[149] also look at hydrological dashboard example from Confederated Salish and Kootenai Tribes of Montana Water Dashboard[150]

[144] National Drought Mitigation Center - University of Nebraska-Lincoln. (n.d.). *What is the USDM*. About. Retrieved October 4, 2022, from https://droughtmonitor.unl.edu/About/WhatistheUSDM.aspx

[145] Ferguson, D. B., A. Masayesva, A. M. Meadow, and M. A. Crimmins, 2016: Rain gauges to range conditions: Collaborative development of a drought information system to support local decision making. *Wea. Climate Soc.,* doi:10.1175/WCAS-D-15-0060.1.; https://wwao.jpl.nasa.gov/water-portfolio/water-projects/nasa-navajo-drought-severity-tool-user-guide/

[146] https://www.usgs.gov/landsat-missions/landsat-9

[147] https://cascprojects.org/#/project/4f8c6580e4b0546c0c397b4e/614ce204d34e0df5fb986940

[148] http://www.tribalwateruse.org/

[149] https://westdaatqa.westernstateswater.org/

[150] https://cskt.aquaticinformatics.net/AQWebPortal

In addition to the examples highlighted using the framework, there are a myriad of other opportunities and needs identified by existing scholarship, research, and activist work in the CRB. The following is a brief outline:

Water access and use

- Help expand the Colorado River Simulation System CRSS[151] to accommodate water accounting, a problem identified by the USBR Ten Tribes Study[152]
- Explore Bureau of Reclamation funding opportunities to partner with Tribes to support more/better data collection and analysis[153]
- Develop household real time monitoring platform for water use and quality to help identify and respond to problems[154]

Drought adaptation

- Predicting water demand scenarios where all Tribal rights are fulfilled, at a Tribe by Tribe level[155]
- Assess groundwater dependent ecosystems, reflecting the growing demand for extracting groundwater in drought conditions[156]
- Agriculture innovations
    - Fallow land monitoring for better water use management[157]
    - Develop/support apps for Indigenous crop management[158]

Mitigation

- Explore/research opportunities to engage in ecosystem based conservation data science projects that can assist Tribes in restoring water supplies

Advocacy for tribal rights and access to water

- Create a database/dashboard of funding opportunities (searchable by eligibility, requirements, etc.) for water access projects[159]
- Review/analyze selection requirements for funding opportunities - scenario modeling to understand impacts if funding was predicated on social outcome versus financial stability[160]
- Data for regeneration - scenario building for the future to include a variety of Tribal values and priorities, E.g., "For example, what would happen if we were to assume that all existing and pending tribal water rights in the basin were fully developed? Or, what would happen if we were to prescribe river ecology goals for different segments of the river system? Should we be modeling for short-term water supply or long-term sustainability (or both)?"[161]

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[151] https://www.usbr.gov/lc/region/g4000/riverops/model-info-APR2018.html

[152] USBR (2018), see Table 9-A

[153] Applied Science Water Smart Grants - https://www.usbr.gov/watersmart/appliedscience/

[154] e.g., see Jimenez, A., Hoefsloot, F. I., & Sara, L. M. (2022). The co-production of the Metropolitan Water Observatory (MWO) platform. KNOW working paper series, (8).

[155] I.e., specify the work on water demand scenarios in USBR (2018) to Tribe specific scenarios for community level planning

[156] Environmental Defense Fund. (N.D). *Groundwater in the Colorado River Basin*. ArcGIS StoryMap. https://storymaps.arcgis.com/stories/c11f7b5fd50644f098497fc7a430a9df

[157] e.g., Norton, C. L., Dannenberg, M. P., Yan, D., Wallace, C. S., Rodriguez, J. R., Munson, S. M., ... & Smith, W. K. (2021). Climate and socioeconomic factors drive irrigated agriculture dynamics in the lower Colorado river basin. *Remote Sensing*, *13*(9), 1659.

[158] Example app - https://cropmanage.ucanr.edu/;

[159] Tanana, H., et al. (2021).

[160] Tracey, J. Colorado Water Center. (personal communication, Sep 16, 2022) discussion on data needs in the basin and the role of funding mechanisms in prioritizing economic gains versus community health gains.

[161] http://www.naturalresourcespolicy.org/docs/colorado-river-basin/basin-report-2020.pdf pg.12

Conclusion

Securing the sustainable use of available, safe, and culturally appropriate water for all has never been more pressing than in a world faced with climate change. And it's not just access that is at risk. Climate change threatens the hydrological cycle the globe over, increasing the likelihood of extreme events and dramatically altered ecosystems, the impacts of which are most felt by those least able to adapt or move away from them. This reality makes the pursuit of water justice a vital goal, one to which data science is uniquely positioned to contribute. However, data science cannot simply apply its tried and true approaches in broad sweeps. Centering justice means centering the expertise and needs of local level actors of a particular water issue. Further, water is a mercurial resource, situated in a hydrosocial landscape, both creating and reflecting local uses and ecosystems as well as responding to the global level drivers of climate change. That makes capturing and utilizing water data in ways that can inform decision making and support justice throughout a particularly challenging prospect.

Using the example of the Colorado River Basin, climate change induced aridification and drought, and the cycle of climate change and water injustices for Tribal communities, this landscape has explored the ways in which data science can attempt to enter into this challenge. Using a scalar, justice-oriented approach as a way to start a data science engagement, focusing typical data science efforts through a lens of justice seeking questions, can provide a starting point to further engage local level experts and needs. The goal is for data science to become a partner in the pursuit of water justice, regardless of the context in which it is applied. That ultimately means adapting approaches based on the voices of those most affected, reorienting the goals for progress to serving their needs and thus making a political assessment about who is centered. This might be a unique, even uncomfortable, prospect given data science is often deployed to achieve large, scalable impacts or to devise broad and generalizable knowledge, trying to remain removed from taking political stances.[162] There may indeed be cases of water justice issues that need such approaches. However, prioritizing local level knowledge and needs first is particularly important when considering the communities who most often suffer from climate change. As discussed in this landscape, these communities have been devalued for so long - through economic, social, political, or bias fueled means - and having data science as a champion versus another way in which they are overlooked, must be the starting point. With this goal as the guide, data science is poised to contribute meaningfully to a wide variety of water justice issues, within the CRB and beyond.

[162] Green, B. (2021). Data science as political action: Grounding data science in a politics of justice. *Journal of Social Computing*, *2*(3), 249-265. https://doi.org/10.23919/JSC.2021.0029

Appendices

A. Importance of Data Sovereignty

As an addendum to the approach provided in this landscape, which focuses on directing data science to contribute to water justice issues, fostering justice *within* data science in the CRB is vital to moving towards a more equitable future for Tribes as well. There is a substantial body of work and scholarship on the concepts of de-colonizing data and supporting Indigenous data sovereignty, in the CRB and across the globe. The key argument of this work is that current, Western produced and oriented data often does not work for Indigenous communities. Depending on data produced by actors that do not have Indigenous values and issues in mind results in: "Inconsistent, inaccurate, and irrelevant data for Indigenous peoples; external control and ownership of data; community mistrust of data resulting from exploitative research and policies; lack of external support for data infrastructure and capability; and, data that describe Indigenous peoples and lifeways through a deficit lens."[163] One of the key ways to address these issues is to build capacity in Indigenous communities themselves to be the primary creators, collectors and managers of data.[164] There are also frameworks to foster Indigenous data sovereignty, for example the CARE principles (Collective Benefit, Authority to Control, Responsibility, and Ethics) developed by key scholars and Indigenous leaders in the field.[165] Additional resources in this area can be found below and are an important place to start when working towards fostering a data science environment itself that is built on justice principles, particularly for Indigenous communities, but also for other communities overlooked by standard data science practice.

- Kukutai, T., & Taylor, J. (2016). *Indigenous data sovereignty: Toward an agenda*. ANU press. https://press.anu.edu.au/publications/series/caepr/indigenous-data-sovereignty
- Carroll, S. R., Herczog, E., Hudson, M., Russell, K., & Stall, S. (2021). Operationalizing the CARE and FAIR Principles for Indigenous data futures. *Scientific Data*, *8*(1), 1-6. https://www.nature.com/articles/s41597-021-00892-0
- Lovett, R., Lee, V., Kukutai, T., Cormack, D., Rainie, S. C., & Walker, J. (2019). Good data practices for Indigenous data sovereignty and governance. *Good data*, 26-36.
- Walter, M., & Suina, M. (2019). Indigenous data, indigenous methodologies and indigenous data sovereignty. *International Journal of Social Research Methodology*, *22*(3), 233-243.https://doi.org/10.1080/13645579.2018.1531228
- Environmental Data Governance Initiative - https://envirodatagov.org/

[163] Carroll, S. R., Rodriguez-Lonebear, D., & Martinez, A. (2019). Indigenous Data Governance: Strategies from United States Native Nations. *Data science journal*, *18*, 31. https://doi.org/10.5334/dsj-2019-031

[164] Ibid.

[165] Carroll, S.R., Garba, I., Figueroa-Rodríguez, O.L., Holbrook, J., Lovett, R., Materechera, S., Parsons, M., Raseroka, K., Rodriguez-Lonebear, D., Rowe, R. & Sara, R. (2020). The CARE principles for indigenous data governance. Data Science Journal, 19: 43, pp. 1–12. DOI: https://doi.org/10.5334/dsj-2020-043

B. Additional Water Data/Science Needs in the CRB

Water Resource Category	Use Case Topics
Snow Properties and Processes	Improved Forecasts of Snowpack, Runoff, Water Demand, and Evapotranspiration
Water Supply Forecasting (< 1 year period)	Timely Streamflow Predictions at Sub-Basin Level
Evapotranspiration (ET) over Land and Water	Consumptive Use for Calculating Water Budgets Quantification of Reservoir Evaporation
Crops and Agriculture Properties and Processes	Crop Mapping Crop Monitoring
Irrigation Types and Methods	Irrigation Management Irrigation Mapping
Groundwater Characterization	Augmenting Groundwater Quantification
Extreme Event Prediction and Impact Assessment	Mitigation of Wildfire Impacts on Watershed Supply Augmentation of State-Level Drought Planning and Response Drought Planning and Response at the State Level
Water Supply Forecasting (≥ 24-month period)	Long-Term Water-Resource Planning: Predicting Changes in the Snowline, Snowpack Distribution, and Streamflow Forecasts

Source: Table 3 from Jenkins, A, Granger, S., Lai-Norling, J., Budney, C., & Johnson, L. (2018). Colorado River Basin Needs Assessment Workshop. NASA Western Water Applications Office. California Institute of Technology, Pasadena, California

C. Other Key Resources

Drought in the CRB - Science and Solutions

- Overview of climate science in the CRB
  - Payton, E. and J. Lukas (2021). Colorado River basin climate and hydrology state of the science: A synthesis report to support water planning and management. Colorado Water, 38:1.https://wwa.colorado.edu/research/projects/colorado-river-basin-climate-and-hydrology-state-science

- Ten Strategies for Climate Resilience in the Colorado River Basin: https://www.tenstrategies.net/
  - Highlights recent Infrastructure Recovery Act funds that can assist

- Recent report on CRB from Bureau of Reclamation:
  - USBR.(2021). Colorado River Basin SECURE Water Act Section 9503(c) Report to Congress. https://www.usbr.gov/climate/secure/docs/2021secure/basinreports/ColoradoBasin.pdf

+ USGS overview of stakeholders and science needs in the CRB:
    - Frus, R.J., Hawbaker, T. J., Anderson, E.D., Anderson, P.J., Andrews, W.J., Bradford, J.B., Dean, D.J., Duniway, M.C., Horton, R.J., Jones, D.K., Monroe, A.P., Qi, S.L., Skinner, C., Thomas, K.A., Tillery, A.C., Torregrosa, A., and Dahm, K.G., 2021, A snapshot of stakeholder science needs related to drought in the Colorado River Basin: U.S. Geological Survey Data Release, https://doi.org/10.5066/P9CTXP26

Tribes and Climate Change in the CRB

+ Status of Tribes and Climate Change Working Group (STACCWG). (2021). Status of Tribes and Climate Change Report, Institute for Tribal Environmental Professionals, Northern Arizona University, Flagstaff, AZ. [Marks-Marino, D. (ed.)] http://nau.edu/stacc2021

+ List of Indigenous projects currently underway via USGS SW Climate Adaptation Science Center (CASC): https://cascprojects.org/#/topics/indigenous-peoples;subtopic=Tribes%20and%20Tribal%20Organizations;type=Project;csc=Southwest%20CASC

Water Justice and Equity

+ Background and current state of Tribal water right settlements
    - Congressional Research Services (2022). Indian Water Rights Settlements. Report to Congress R44148. https://crsreports.congress.gov/product/pdf/R/R44148

+ DigDeep, & U.S. Water Alliance. (2019). *Closing the water access gap in the United States: A National action plan*. https://www.digdeep.org/s/Dig-Deep_Closing-the-Water-Access-Gap-in-the-United-States_DIGITAL_compressed-2hyx.pdf

+ Tribal Access to Clean Water Bill: https://www.congress.gov/bill/117th-congress/senate-bill/2369
    - Introduced summer of 2021, not yet passed

+ Review of Water Data in the U.S.:
    - Marston, L. T., Abdallah, A. M., Bagstad, K. J., Dickson, K., Glynn, P., Larsen, S. G., Melton, F.S., Painter, J.A., Prairie, J., Ruddell, B.J., Rushforth, R.R., Senay, G.B., & Shaffer, K. (2022). Water-Use Data in the United States: Challenges and Future Directions. *JAWRA Journal of the American Water Resources Association*.

+ Data Capacity and Environmental Justice Organizations:
    - Martín, C. (2021). *The Landscape of Data Capacity in US Environmental Justice Organizations*. The Urban Institute. https://www.urban.org/research/publication/landscape-data-capacity-us-environmental-justice-organizations